DTU Library

Hot water tanks for solar heating systems

Furbo, Simon

Publication date:
2004

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Furbo, S. (2004). *Hot water tanks for solar heating systems*. DTU Byg, Danmarks Tekniske Universitet. Byg Rapport No. R-100 http://www.byg.dtu.dk/publications/rapporter/byg-r100.pdf

HOT WATER TANKS
FOR
SOLAR HEATING SYSTEMS

REPORT NO. R-100

JUNE 2004

SIMON FURBO
Department of Civil Engineering

CONTENTS

SUMMARY

The hot water tanks used today in Danish marketed SDHW systems are described. Both the design and the most important thermal data of the tanks are given.

By means of detailed simulation programs the annual thermal performance of small SDHW systems have been calculated for Danish conditions. The solar heating systems are using differently designed hot water tanks as heat storage.

Two types of solar heating systems were investigated in this way. A traditional solar heating system based on one hot water tank, the so-called combi store, heated both by the solar collector and by the auxiliary energy supply system(s), and a solar heating system with a heat storage consisting of two hot water tanks: a preheater, only heated by the solar collector and an existing hot water tank, heated by a modern energy supply system with a small standby heat loss.

Two types of hot water tanks were investigated: A mantle tank and a hot water tank with a built-in heat exchanger spiral. The mantle tank is part of a low flow solar heating system and the spiral tank is part of a traditional solar heating system with a high volume flow rate in the solar collector loop.

By means of the calculations it has been elucidated how the design of hot water tanks influence the thermal performance of solar heating systems. Based on these calculations, guidelines for design of hot water tanks for SDHW systems have been established.

1. INTRODUCTION

The storage tank is the component that is most important for the price and performance of the small SDHW systems. E.g., measurements on eight marketed systems show that the thermal performance of the system is primarily determined by the design of the hot water tank, [1].

A recently completed project has given a survey of the solar heating systems that have been installed during the last few years [2]. On the basis of this project, it can be conclude that in future there will be a demand for three different types of hot water tanks for SDHW systems:

1. **Combi store**, which can be heated both by solar collectors and by auxiliary energy supply system(s). For about 75% of the solar heating systems installed these years, the combi store is the most suitable solution. Today this type of storage tank is used in almost all small solar heating systems.
2. **Pre-heater**, which is only heated by solar collectors. The solar heating system is based on a pre-heater and an existing hot water tank. The domestic water is heated by the solar collectors in the pre-heater, and, if necessary, a back-up energy system with a small standby loss will heat the domestic water in an existing hot water tank to the desired tapping temperature. The volume of the pre-heater is smaller than the volume of the combi store. In about 25% of the solar heating system installed at present, the pre-heater solution would be attractive. [2].
3. **Hot water tank prepared for solar heating systems.** This storage type can typically be designed like the combi store so that the tank can be heated both by the primary energy source and by solar collectors that will be installed at a later date.

The combi store and the pre-heater are in Denmark marketed in two versions: The hot water tank with and without a unit with all the necessary auxiliary equipment for the solar heating system, such as pump, control system etc. The hot water tank prepared for solar heating does not contain this auxiliary equipment.

On the basis of existing knowledge of hot water tanks and calculation results from existing detailed simulation models for solar heating systems, this report describes how to design hot water tanks for small solar domestic hot water systems in the best way. It is only described how the hot water tanks – combi stores as well as pre-heaters – should be designed. In [3], which deals with the installation and corrosion conditions for small solar heating systems, it is described how to design and install the auxiliary equipment for the solar heating system in the best way.

2. MARKETED COMBI STORES IN APPROVED SOLAR HEATING SYSTEMS

This chapter contains a statistical examination of the design of small combi stores in approved solar domestic hot water systems on the Danish market at the beginning of 1995. The investigation deals with the following hot water tanks.

ID No.	Manufacturer	Type*	Volume
D3020	Kähler & Breum K/S	spiral	255
D3029	Aidt Miljø A/S	mantle	265
D3032	Uniterm	spiral	275
D3034	Ar-Con Solvarme A/S	spiral	250
D3042	Vølund A/S	spiral	200
D3043	KN Smede- og Beholderfabrik A/S	spiral	500
D3045	HS Kedler - Tarm	spiral	290
D3046	Nilan A/S	spiral	180
D3047	IPL	mantle	260
D3048	Nilan A/S	spiral	180
D3049	Nilan A/S	spiral	280
D3050	Fønix Staalindustri A/S	spiral	300
D3051	Fønix Staalindustri A/S	spiral	160
D3055	Aidt Miljø A/S	mantle	200
D3056	Nilan A/S	spiral	180
D3057	KN Smede- og Beholderfabrik A/S	spiral	500
D3058	Uniterm	spiral	525
D3060	Aidt Miljø A/S	mantle	460
D3061	Nilan A/S	mantle	200

Table 1. Small hot water tanks in approved solar domestic hot water systems. *Type of solar heat exchanger.

The following examination of the tanks has been carried out on the basis of available information on the tanks from test reports, manufacturers, VA-approvals, installation manuals, instructions, user manuals etc. It has not been possible to achieve an equally high level of information for all the tanks. Half of the 19 tanks in table 1 have been tested at The Danish Solar Energy Testing Laboratory.

The investigation only includes vertical mantle tanks. Horizontal mantle tanks are normally only used in thermosyphoning systems for which there is almost no market in Denmark.

15 spiral tanks and 4 mantle tanks are a slender foundation for the execution of a statistical analysis. The results are therefore somewhat uncertain, especially for the parameters that do not have information on all the tanks.

The typical hot water tank

On the basis of tank data, this part describes a typical tank in a small Danish SDHW system. A distinction is made between spiral tanks and mantle tanks. To a large extent, the following typical tanks have been found as an average of the tanks from table 1.

The typical spiral tank

Tank:	Volume:	290 litres	
	Height/diameter ratio:	2.6$^+$ (2.8 for tanks of 250-300 litres)	
	Material:	Steel 37-2	
	Cold water inlet:	Through bottom with baffle plate	
	Hot water outlet:	PEX pipe from top through bottom	
	Corrosion protection:	Enamel + magnesium anode	
Insulation:	Material:	Polyurethane foam	250-300 litres*
	Insulation thickness – sides:	57 mm	49 mm
	Insulation thickness – top:	86 mm	75 mm
	Insulation thickness – bottom:	31 mm	28 mm
	Heat loss coefficient – stand by:	1.9 W/K	1.7 W/K
	Heat loss coefficient – operation:	2.8 W/K	2.4 W/K
Solar heat exchanger:	Length:	11 m	
	Outer pipe diameter:	18 mm => 0.63 m^2	
	Height of heat exchanger:	Top: 81 litres from the bottom	
	Volume under heat exchanger/Dead volume:	17 litres	
	Material:	Enamelled steel/stainless steel	
	Pipe connections:	Through bottom	
Auxiliary heat exchanger:	Exactly like the solar heat exchanger		
	Location:	Heats 95 litres	
	Pipe connection:	⅔through the side (in tank insulation to bottom) and ⅓through bottom	
Electric heating element:	Power:	1 kW/230V, 3 kW/400 V	
	Location:	Heats 90 litres	
Auxiliary equipment:	Location:	Under the tank	

+ The mean values are determined on the basis of all the tanks with volumes between 180 l and 525 l.

* The mean values, determined on the basis of all the tanks, include data for tanks of about 500 litres, which normally have a thicker insulation layer, but also a larger heat loss.

The typical mantle tank

Tank:	Volume:	275 litres + 15 litres in the mantle
	Height/diameter ratio:	2.6^{+} (3 for tanks of 250-300 litres)
	Material:	Steel 37-2
	Cold water inlet:	Through bottom with baffle plate
	Hot water outlet:	PEX pipe from top through bottom
	Corrosion protection:	Enamel + magnesium anode
Insulation:	Material:	Polyurethane foam
	Insulation thickness – sides:	52/65 mm*
	Insulation thickness – top:	93 mm
	Insulation thickness – bottom:	25 mm
	Heat loss coefficient –stand by:	1.8 W/K
	Heat loss coefficient – operation:	2.2 W/K
Solar heat exchanger:	Height of heat exchanger:	The top: 157 litres from the bottom
	Heat transfer area:	1.1 m^2
	Volume under heat exchanger/Dead volume:	18 litres
	Material:	Steel
	Pipe connections:	Through the side (in the tank insulation to bottom)
Auxiliary heat exchanger:	Length:	10 m
	Pipe dimension:	$^3/_4$" => 0.62 m^2
	Material:	Enamelled steel
	Location:	Heats 93 litres
	Pipe connection:	Through the side (in tank insulation to bottom)
Electric heating element:	Power:	1 kW/230V, 3 kW/400 V
	Location:	Heats 96 litres
Auxiliary equipment	Location:	Under the tank

+ The mean values are determined on the basis of all the tanks with volumes between 200 l and 460 l.

* Smallest thickness on the level with the mantle and larges thickness on the level with the top of the tank (without mantle).

From the above it can be seen that, on the whole, there is no difference between a spiral tank and a mantle tank, leaving out of account the solar heat exchanger. The typical tanks are reported as "mean values" for several tanks. Therefore, the mean values cover the dispersion of the values existing between the single tanks. The dispersion for single parameters is shown in the following figures.

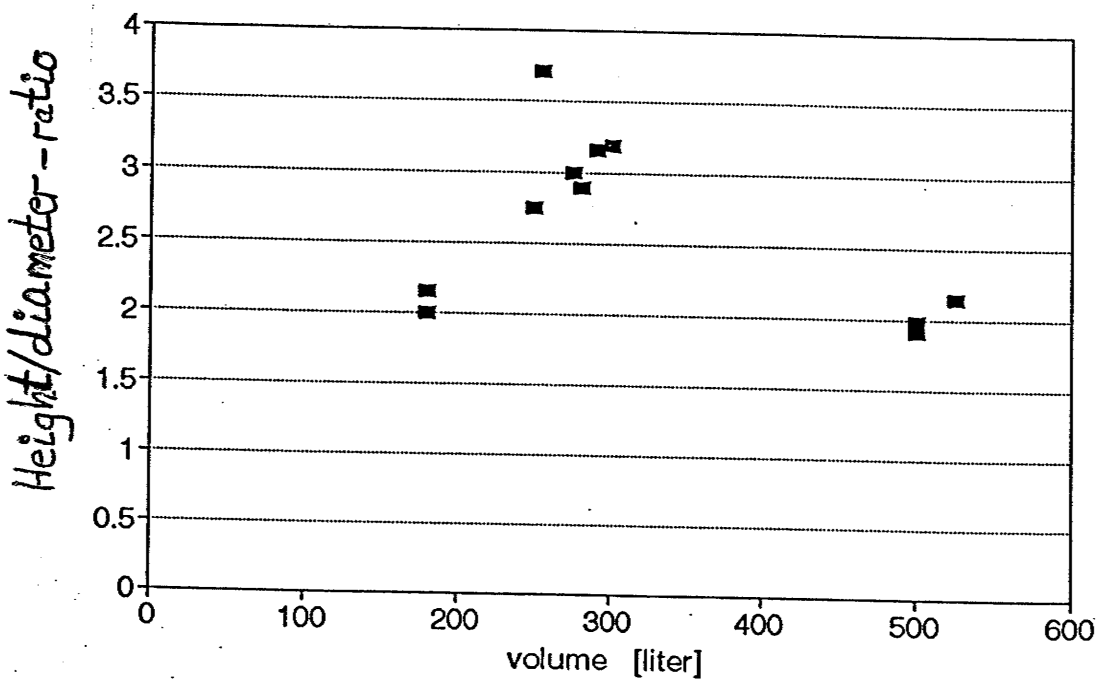


Figure 1. The height/diameter ratio for the spiral tanks as a function of the tank volume.

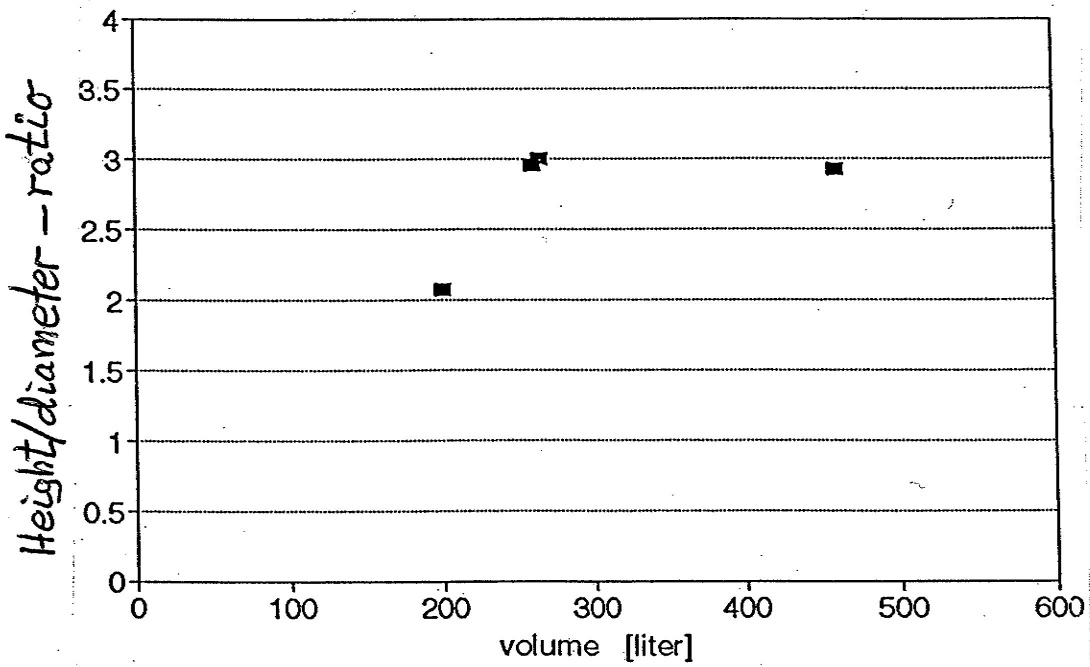


Figure 2 The height/diameter ratio for the mantle tanks as a function of the tank volume.

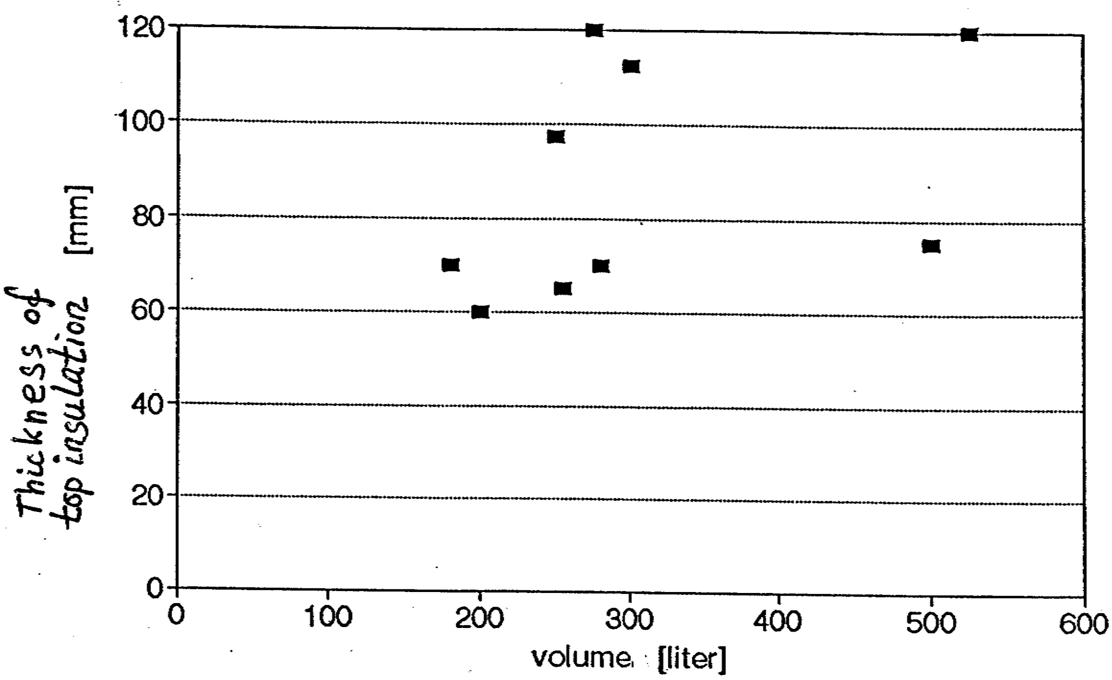


Figure 3. The thickness of the top insulation for the spiral tanks as a function of the tank volume.

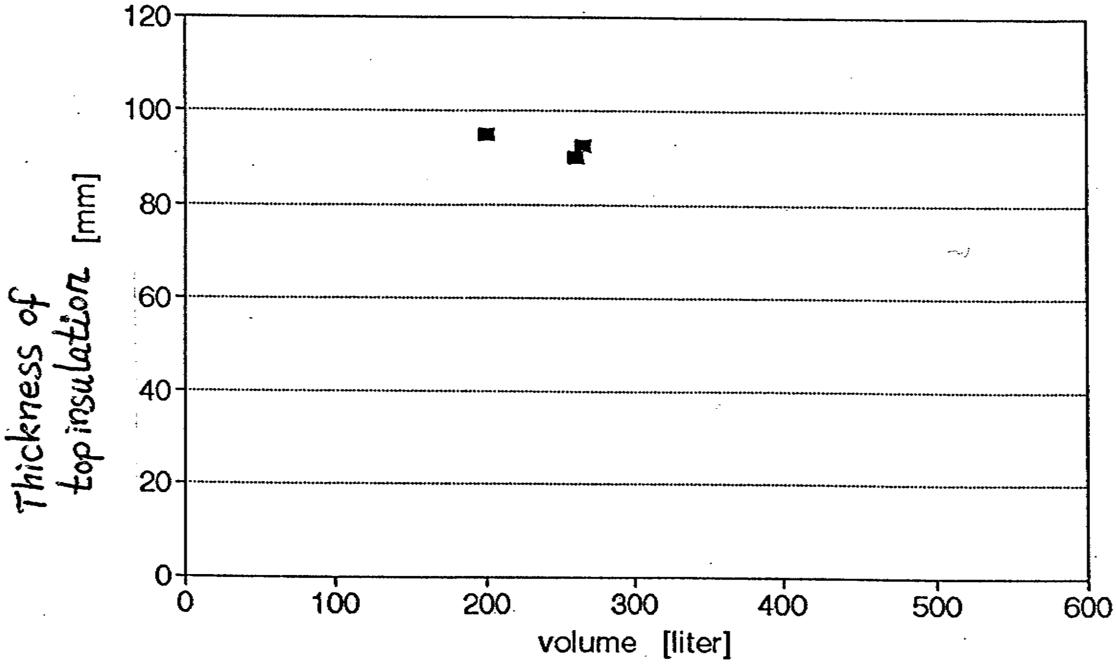


Figure 4. The thickness of the top insulation for the mantle tanks as a function of the tank volume.

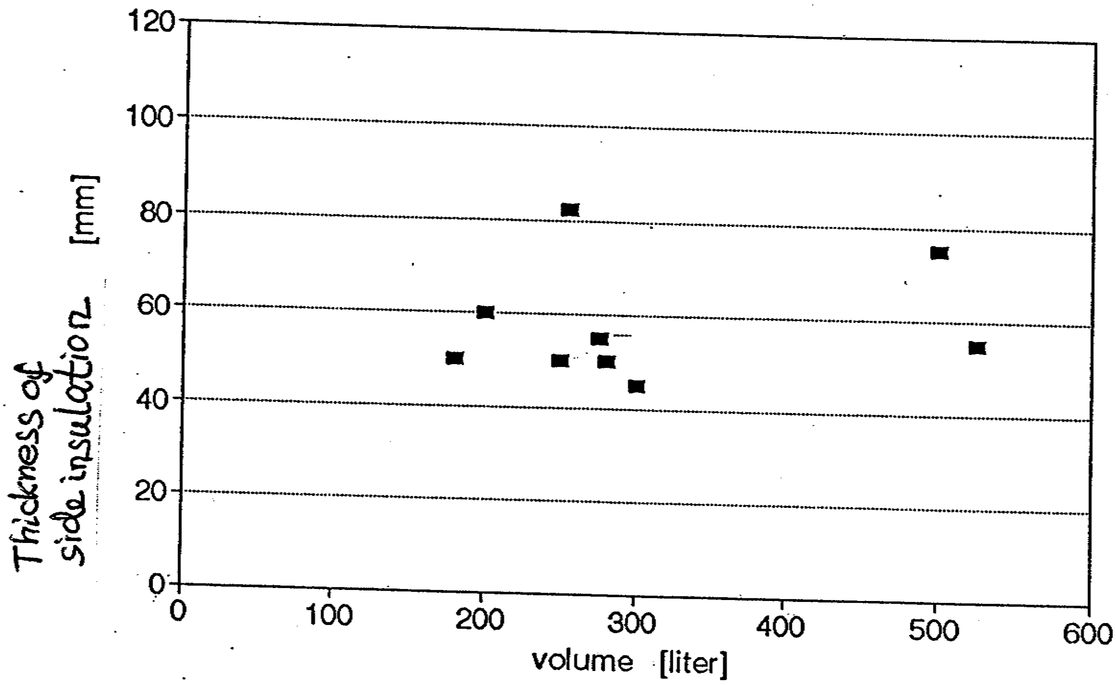


Figure 5. The thickness of the side insulation for the spiral tanks as a function of the tank volume.

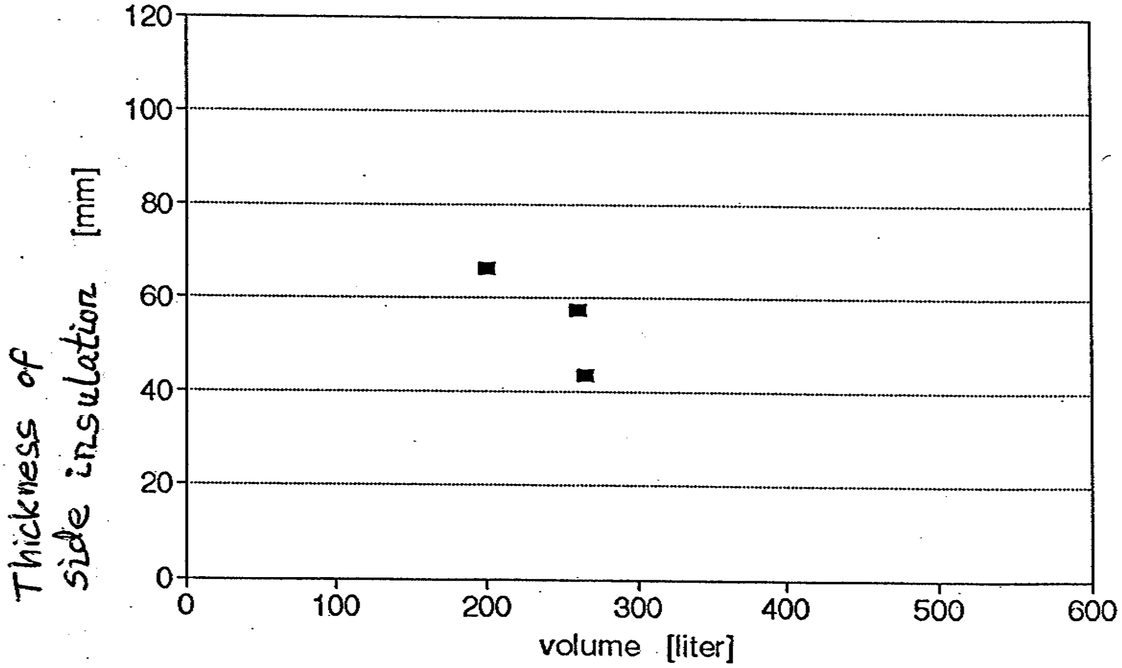


Figure 6. The thickness of the side insulation for the mantle tanks as a function of the tank volume.

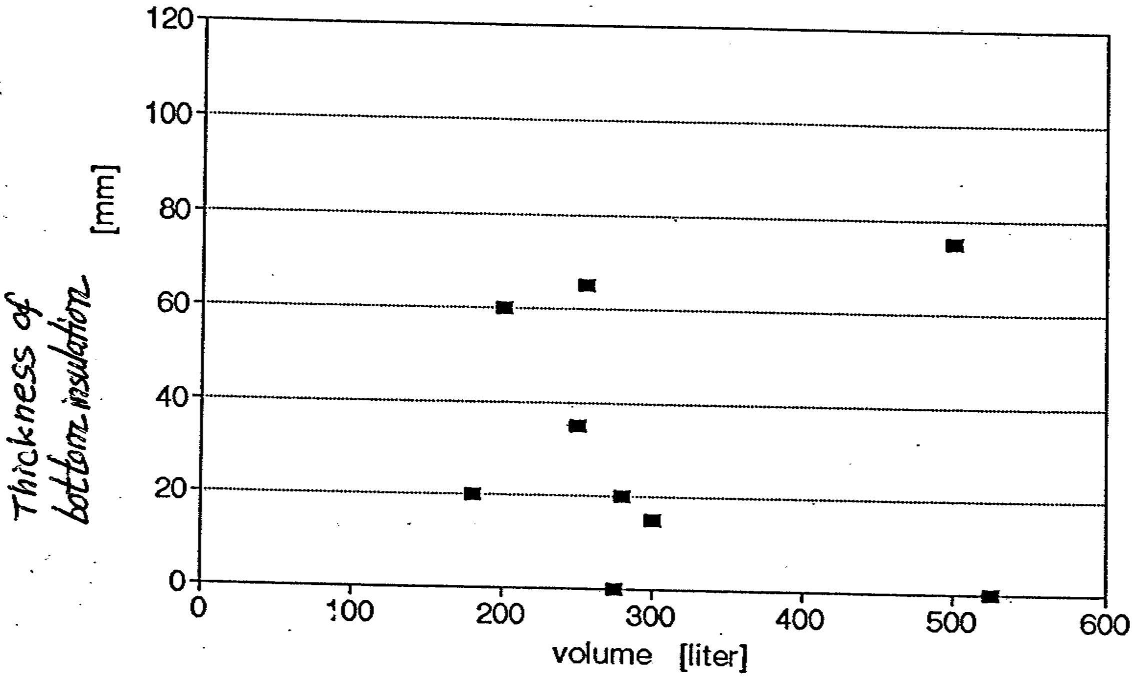


Figure 7. The thickness of the bottom insulation for the spiral tanks as a function of the tank volume.

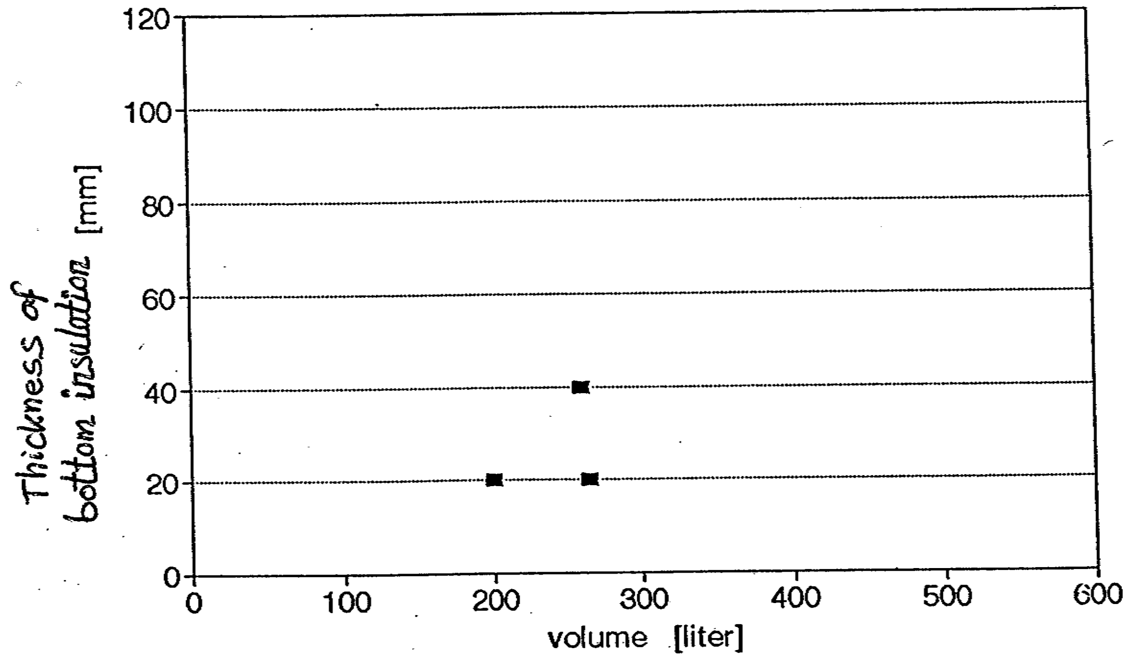


Figure 8. The thickness of the bottom insulation for the mantle tanks as a function of the tank volume.

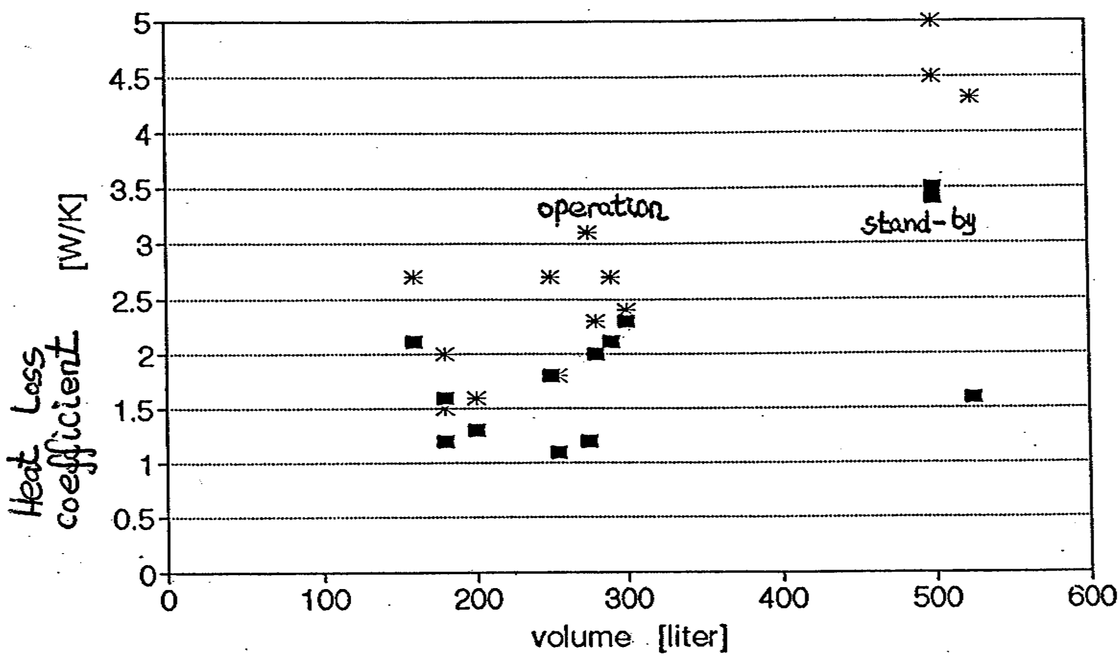


Figure 9. The heat loss coefficient for the spiral tanks as a function of the tank volume.

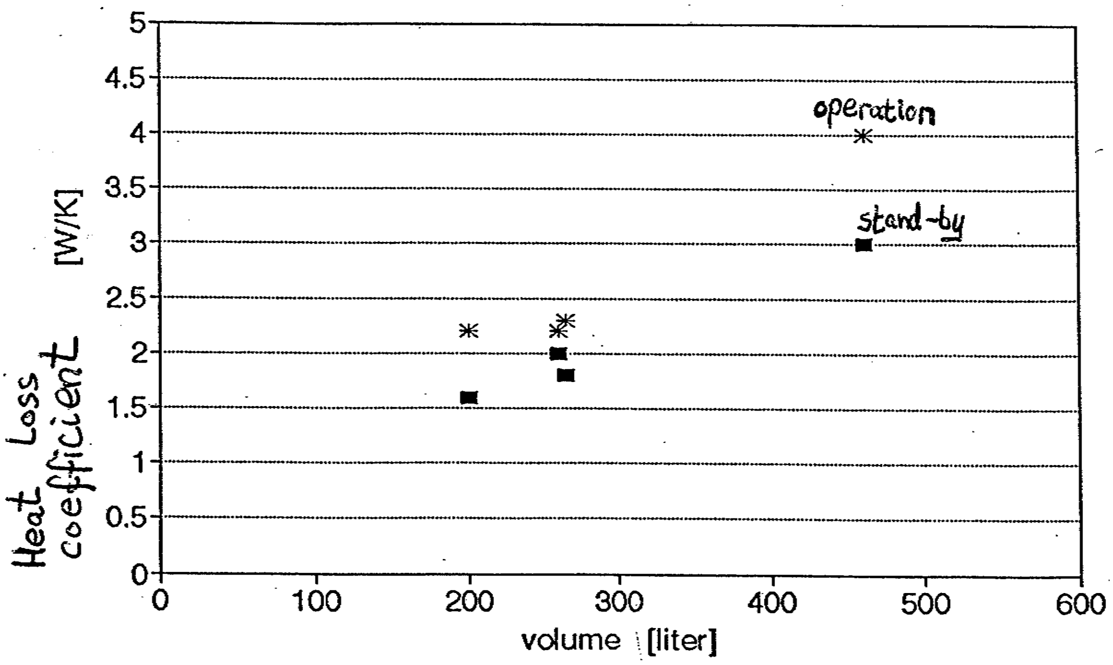


Figure 10. The heat loss coefficient for the mantle tanks as a function of the tank volume.

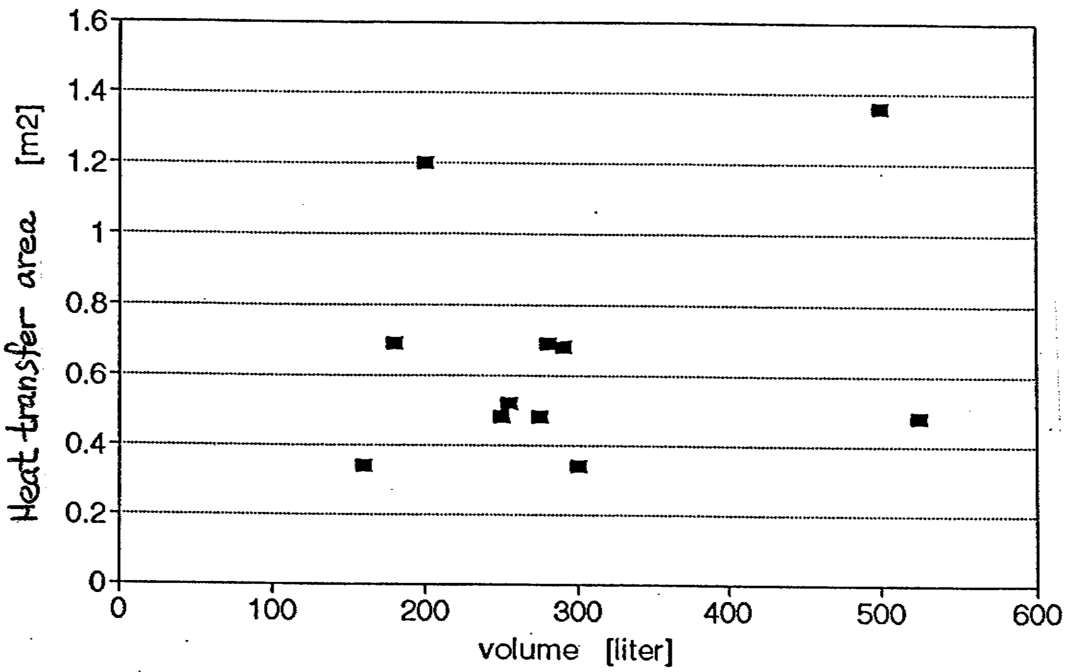


Figure 11. The heat transfer area of the solar heat exchanger in the spiral tanks as a function of the tank volume.

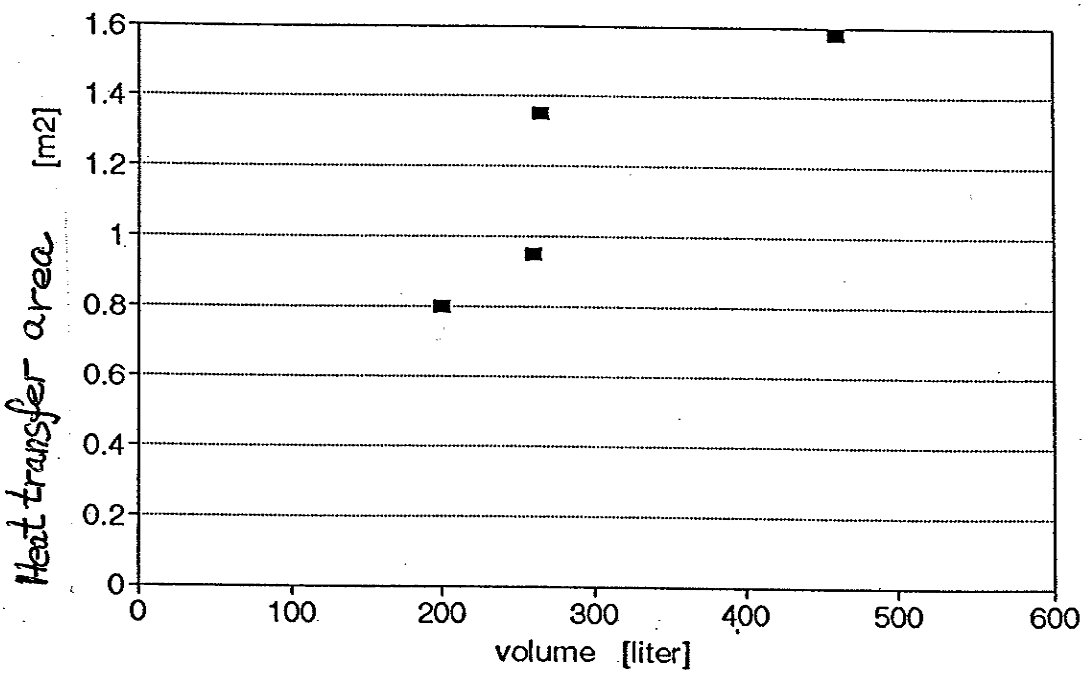


Figure 12. The heat transfer area of the solar heat exchanger in the mantle tanks as a function of the tank volume.

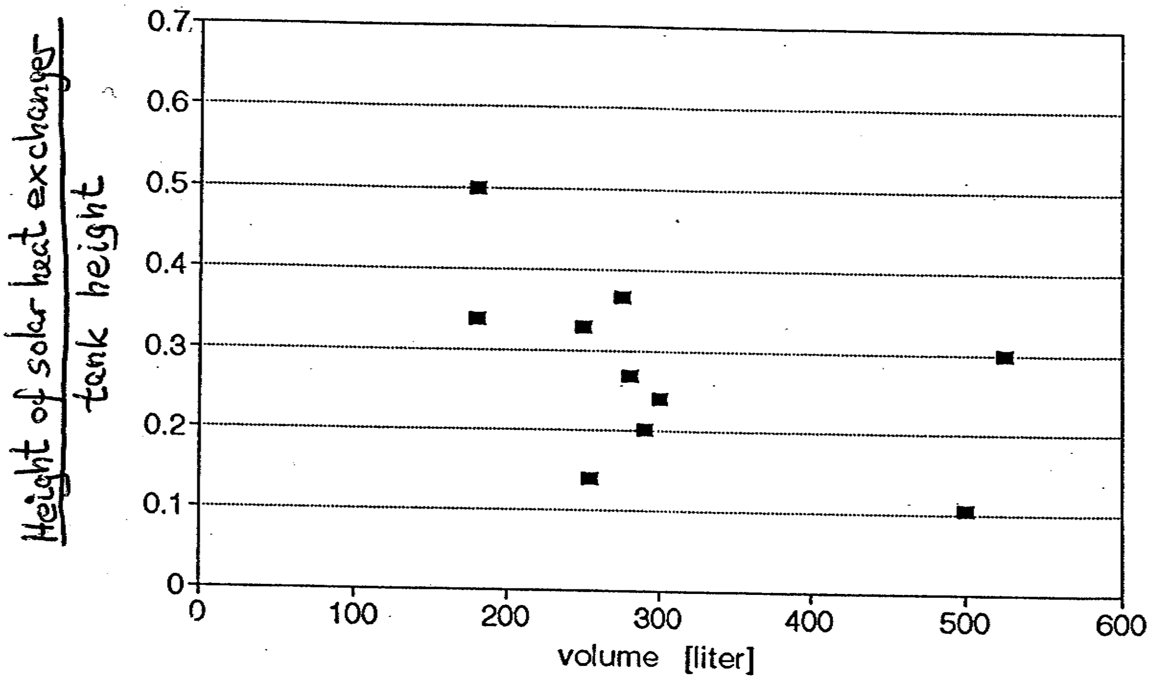


Figure 13. The height of the solar heat exchanger in the spiral tanks as a function of the tank volume.

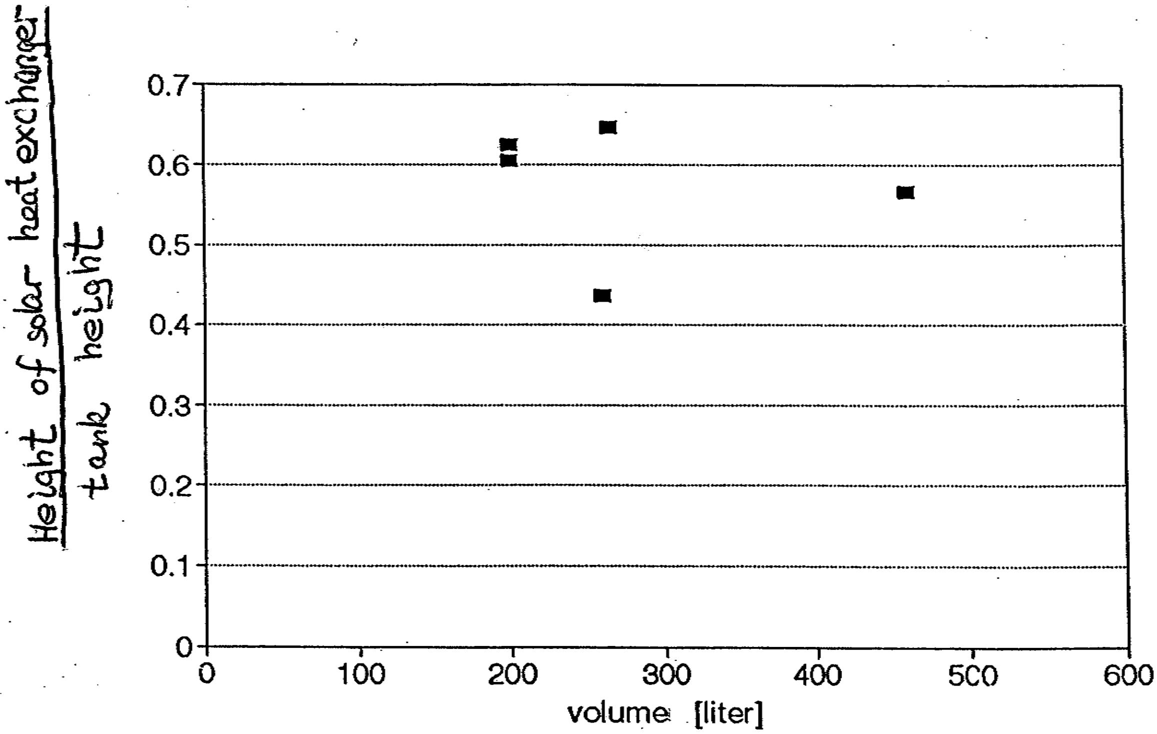


Figure 14. The height of the solar heat exchanger in the mantle tanks as a function of the tank volume.

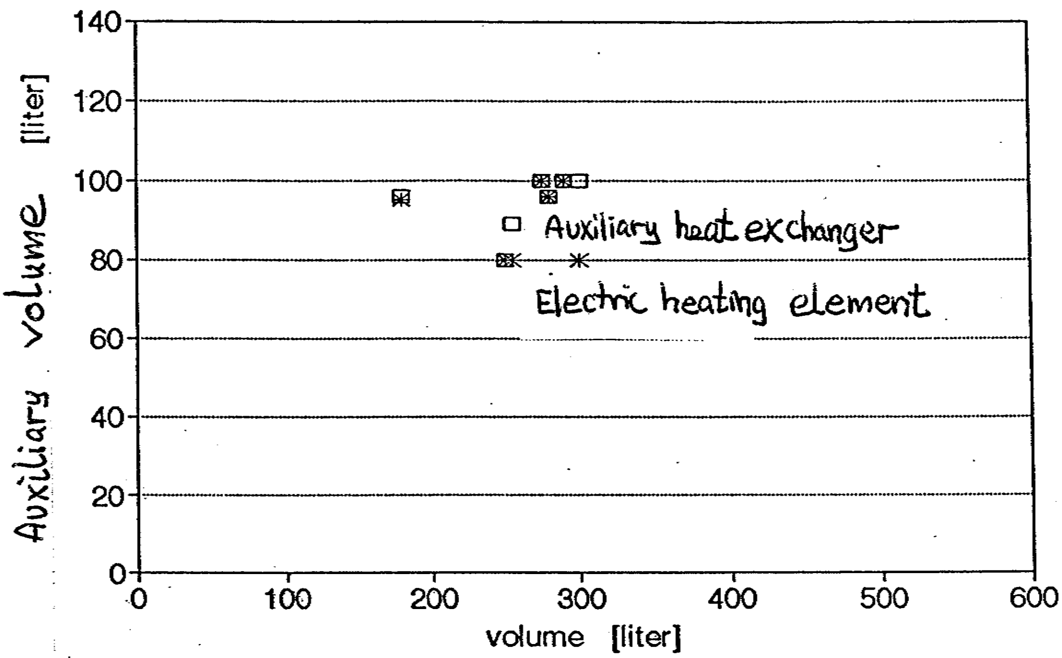


Figure 15. The volume heated by the auxiliary heat exchanger and the electric heating element in the spiral tanks as a function of the tank volume.

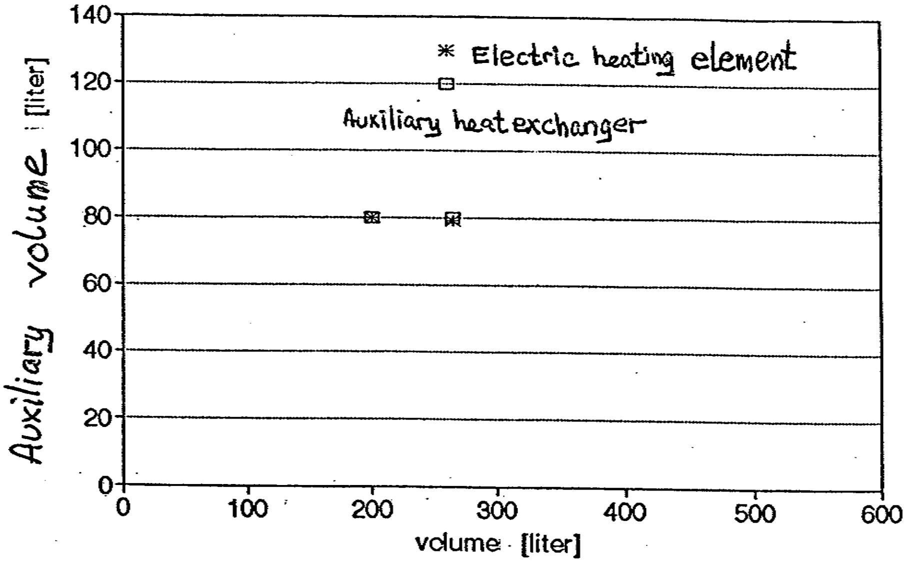


Figure 16. The volume heated by the auxiliary heat exchanger and the electric heating element in the mantle tanks as a function of the tank volume.

Figures 1-2 show that the height/diameter ratio for tanks of 250-300 litres is around 3, whereas this ratio for large and small tanks is around 2. The smaller height/diameter ratio for small tanks is due to the fact that the same end bottoms are used as for the tanks of 250-300 litres, which often have a diameter of 0.5 m. The small tanks are therefore not particularly high. For the larger tanks of about 500 litres the height of the room is the limiting factor. Investigations show, see chapter 3, that a good thermal stratification for spiral tanks is obtained when the height/diameter ratio is 2 or higher. The height/diameter ratio is thus equal to or higher than the recommended ratio. For mantle tanks in low flow systems it is recommended that the height/diameter ratio is as large as practically possible.

Figures 3-8 show the insulation thickness of the tanks. The given thickness values are mean values as the end bottoms are convex and the outer circumference of the side insulation is often octagonal.

Figure 3 shows that the top insulation of the tanks is increased with the volume of the tank. This is a wise measure, as a poor insulation is comparatively significant in the top - especially when it is about large tanks with a small height/diameter ratio. Figures 5-6 show that, on the whole, the side insulation is independent of the tank volume. Figures 7-8 show that the thickness of the bottom insulation varies much from tank to tank. It is often recommended to omit the bottom insulation, as there is only an insignificant heat loss through the bottom of the tank. Furthermore, omission of the bottom insulation can reduce the risk that the system begins to boil in hot periods without tappings. At the same time, however, the condensation is increased and with that the risk of external corrosion of the tank bottom. Most of the tanks have bottom insulation. This is due to the fact that most of the tanks are insulated with foam that is supplied to the tank by covering the tank with a mould. The space between the mould and the tank is then filled with foam. Preferably, the mould must be completely tight. This is best achieved by letting it surround the whole tank - also the bottom. The ratio between the top and bottom thickness can be regulated by displacing the tank in the mould, which has the effect that there will often be a little insulation at the bottom of the tank, anyway.

Figure 9-10 shows the heat loss coefficients of the tank at standstill and in operation. As anticipated the heat loss increases with increased tank size. There is, however, a large dispersion in the single tank volumes. The figures show that it is possible to reach a very low heat loss if the tank, insulation and pipe connection are designed correctly. The theoretical heat loss coefficient without thermal bridges for a 250-300 litres spiral tank is 1.3 W/K (with the given insulation thicknesses from the table for the typical spiral tank). For the investigated tanks with a volume of 250-300 litres, the average heat loss during operation (2.4 W/K) is about 85% higher than the theoretical heat loss. Thus, it is possible to reduce the heat loss of the tanks further and in that way increase the performance of the solar heating systems.

Generally, the heat transfer area increases with the tank size - Figure 11-12. There is, however, a small tank with a large heat transfer area and a large tank with a small heat transfer area. The heat transfer area is larger for the mantle tanks than for the spiral tanks.

Figure 13-14 shows that only a few solar heat exchangers of the spiral type are higher than a third of the tank height, whereas the height of the mantles are often two thirds of the tank height.

Figure 15-16 shows that generally the tank manufacturers agree that the volume for supplementary energy should be between 80 and 100 litres - only one manufacturer has a volume of more than 100 litres. Investigations have shown that a supplementary volume of 60 litres will often be sufficient to maintain the comfort level - especially in dwellings without a bath tub. The manufacturers choose to be on the safe side, however. This reduces the performance of the solar heating systems by about 1-2% for a tank of 300 litres [4]. This performance reduction is increased with increasing auxiliary volume and decreasing tank volume - the performance reduction for solar heating systems with a tank of 200 litres is thus around 10%, see chapter 3.

3. CALCULATED PERFORMANCE FOR SOLAR HEATING SYSTEMS WITH DIFFERENT HOT WATER TANKS

The annual performance for small solar domestic hot water (SDHW) systems has been calculated with detailed simulation models under typical conditions. Calculations have been carried out for solar heating systems with a combi tank that can both be heated by solar collectors and by the auxiliary energy supply system. Furthermore, calculations have been carried out for preheating systems that are based on a pre-heater heated by solar collectors and an existing hot water tank heated by a modern back-up energy system with a small standby loss.

As a starting point for the calculations, two reference systems have been chosen; a traditional solar heating system with a high volume flow rate in the solar collector loop and a hot water tank with a built-in heat exchanger spiral, and a low flow solar heating system with a mantle tank.

The calculations have been carried out with differently designed hot water tanks. By this it was elucidated how the design of the hot water tanks influences the performance of small solar heating systems.

3.1 Calculation assumptions

Data of the hot water tanks of the two reference systems appear from table 2. The rest of the data of the two reference systems, which are maintained in all calculations, appear from table 3.

The daily hot-water consumption of 160 l and the draw-off pattern that are used in the calculations appear in table 4.

For the traditional solar heating system with a hot water tank with a built-in heat exchanger spiral, the detailed simulation model developed in [5] is used for the performance calculations. The heat exchange capacity rate at the heat exchanger spiral is heavily dependent on the operation conditions. The heat exchange capacity rate at the different operation conditions is determined by means of the method developed in [6].

For the low flow system with a mantle tank, the detailed simulation model developed and validated in [7] and [8] is used.

Tank type	Mantle tank	Hot water tank with built-in heat exchanger spiral
Tank material	St 37-2	St 37-2
Hot water tank		
volume	192 l	194 l
height/diameter	1020/500 mm	1020/500 mm
wall thickness Sides	4 mm	3 mm
Top and bottom	4 mm	4 mm
Mantle		
volume	81	
height/diameter	463 mm/530 mm	
thickness	4 mm	
place	The mantle surrounds the lowest part of the hot water tank. The upper 96 l and the lower 10 l of the tank are not surrounded by the mantle.	
Heat exchanger spiral		
material		St 37-2
dimension		½"
length		12 m
place		Heat exchanger spiral placed at the bottom of the hot water tank
Auxiliary energy supply systems		
place and control system	The upper 96 l of the hot water tank are heated to 50.5°C by the auxiliary energy supply system(s).	The upper 97 l of the hot water tank are heated to 50.5°C by the auxiliary energy supply system(s).
Insulation and heat loss		
insulating material	PUR foam	PUR foam
insulation thickness	50 mm around the upper half and the lower 10 l of the hot water tank 35 mm around the mantle and the bottom of the hot water tank	50 mm
thermal bridge at the bottom of the tank	0.5 W/K	0.5 W/K
the heat loss coefficient of the		

hot water tank at 60°C	1.8 W/K	1.6 W/K

Table 2. Data of the hot water tanks of the two reference systems.

Hot-water consumption: 160 l/day heated from 10°C to 50°C			
Draw-off time	7 a.m.	12 noon	7 p.m.
Draw-off volume	53.33 l	53.33 l	53.33 l

Table 4. Hot-water consumption and draw off pattern used for calculating thermal performance of the system.

SOLAR COLLECTOR

SOLAR COLLECTOR AREA: 4 M^2

SOLAR COLLECTOR EFFICIENCY AT SMALL INCIDENCE ANGLES: $\eta = 0.75 - 5.40 \cdot (T_m - T_{ude})/I$

HEAT CAPACITY OF THE SOLAR COLLECTOR: 7000 J/M^2K

TILT OF THE SOLAR COLLECTOR: 45 °

ORIENTATION OF THE SOLAR COLLECTOR: FACING SOUTH

CONTROL SYSTEM

DIFFERENTIAL THERMOSTAT CONTROL WITH A SENSOR IN THE SOLAR COLLECTOR AND A SENSOR IN THE BOTTOM OF THE MANTLE AND IN THE BOTTOM OF THE SPIRAL TANK, RESPECTIVELY.

START AND STOP DIFFERENCES: $\begin{cases} \text{5 K AND 2 K FOR THE MANTLE TANK} \\ \text{5 K AND 0.4 K FOR THE SPIRAL TANK} \end{cases}$

VOLUME FLOW IN SOLAR COLLECTOR LOOP: $\begin{cases} \text{0.6 L/MIN FOR THE MANTLE TANK} \\ \text{4.0 L/MIN FOR THE SPIRAL TANK} \end{cases}$

SOLAR COLLECTOR LOOP

PIPE MATERIAL: COPPER

OUTER DIAMETER: 15 MM

INNER DIAMETER: 13 MM

INSULATING MATERIAL PUR FOAM

INSULATION THICKNESS 10 MM

LENGTH OF PIPE FROM COLLECTOR TO STORAGE, OUTDOORS 1.5 M

LENGTH OF PIPE FROM STORAGE TO COLLECTOR, OUTDOORS 1.5 M

LENGTH OF PIPE FROM COLLECTOR TO STORAGE, INDOORS 3.5 M

LENGTH OF PIPE FROM STORAGE TO COLLECTOR, INDOORS 3.5 M

SOLAR COLLECTOR FLUID: 50% (WEIGHT%) PROPYLENE GLYCOL/WATER-MIXTURE

POWER OF CIRCULATION PUMP: 30 W
HEAT STORAGE
AMBIENT TEMPERATURE: 20°C

Table 3. Data of the reference systems.

The simulation models cannot simulate the thermal conditions in hot water tanks completely correct. The calculations are therefore made on the following assumptions:

- pipe connections do not cause any thermal bridges in the top of the tanks.
- the systems are not provided with circulation pipes.
- auxiliary energy supply system(s) heats (heat) the whole top of the tanks to the same temperature level.
- no undesirable mixing in the tanks owing to heating - either from solar collectors or from auxiliary energy supply system(s) - occurs.
- no mixing occurs in the tanks during hot-water tappings.
- no downward heat transfer in the tanks owing to vertical pipes and heat exchanger spirals occurs, either when fluid flows in the pipes/spirals or when the fluids are stagnant.
- the heat transfer conditions for mantle tanks are determined by measurements on a 200 l standard mantle tank.

The above-mentioned conditions can be very important for the thermal stratification in hot water tanks and thus for the performance of solar heating systems. There is, therefore, a need to develop the simulation models further, so that the thermal stratification in hot water tanks can be calculated correctly from knowledge of the detailed tank designs. It is outside the framework of this project to develop the simulation models further. Therefore, certain reservations must be made for the calculation results in this project.

The weather data of the Danish reference year [9] has been used for the calculations. The data given in table 3 are used in the calculations. The tank designs are determined by a number of parameters. The parameters for the hot water tanks of the reference systems appear from table 2. The influence on the solar heating system performance has been calculated with different sizes of a single parameter that have a say in the tank design. Apart from variations of the size of this single parameter, data from table 2 have been used. I.e. one parameter varied at a time.

3.2 Calculation Results

The calculated yearly thermal performance of the reference systems appears from table 5. The net utilized solar energy of the combi tank system is defined as the tapped energy quantity from the combi tank minus the energy supplied to the auxiliary energy supply system. The net utilized solar energy of the preheating system is defined as the tapped energy quantity from the preheating system. The solar fraction is the ratio between the net utilized solar energy and the hot-water consumption, which is 2690 kWh/year, corresponding to the hot-water consumption of 160 l/day heated from 10°C to 50°C.

Tank / System type	Spiral tank		Mantle tank	
	Net utilized solar energy	Solar fraction	Net utilized solar energy	Solar fraction

Combi tank system	1150 kWh/year	43%	1270 kWh/year	47%
Preheating system	1390 kWh/year	52%	1510 kWh/year	56%

Table 5. Calculated annual net utilized solar energy and solar fraction of the 4 reference systems.

It appears that the thermal performance of the preheating systems is about 20% greater than the thermal performance of the combi tank systems. The main cause for this increase in performance is that, as a rule, the temperatures in the pre-heaters are much lower than the temperatures in the combi tanks. Besides the pre-heater, preheating systems are normally also supplied with an existing hot water tank heated by the auxiliary energy supply system. The existing hot water tank has a heat loss that is not included in the performance specifications in this report. In practice, the performance of the two system types will be almost identical.

Further, it appears that low flow systems with mantle tanks perform about 10% more than traditional systems with spiral tanks. Investigations have shown that the increase in thermal performance for low flow systems greatly depends on the solar fraction [8], [10]. The smaller the solar fraction, the larger is the increase in thermal performance for low flow systems.

Measurements have shown that for combi tank systems, a standard low flow system will annually perform about 17% more than a traditional solar heating system when the solar fractions of the two systems are about 48% and 41%, respectively [11]. Consequently, the calculated increases in thermal performance for low flow systems are somewhat smaller than the measured increases. The main causes for the difference between calculated and measured increases in performance are probably two of the calculation assumptions given in paragraph 3.1. In spiral tanks, in certain periods, undesirable mixing will occur between the solar-heated water at the bottom of the tanks and the warmer water above heated by the auxiliary energy supply system. How much this mixing, which is not taken into calculation, reduces the performance of the traditional solar heating system depends on the design of the heat exchanger spiral. Investigations of a marketed tank have shown a reduction in performance of about 4% caused by this mixing [12]. Furthermore, the downward heat transfer through the heat exchanger spiral will also reduce the thermal performance of the traditional solar heating system. As mentioned in paragraph 3.1, this heat transfer is not taken into calculation either.

It should therefore be noted that the calculations somewhat underestimate the performance advantages of low flow systems with mantle tanks. It is estimated, however, that the simulation models can reasonably be used for the parameter analysis mentioned below.

Figures 17-33 show the calculation results. The annual net utilized solar energies and the relative performances, both for combi tank systems and for preheating systems, are shown as a function of the varied parameter size both for mantle tank systems and for spiral tank systems. The relative performance is defined as the ratio between the net utilized solar energy of the system in question and the net utilized solar energy of the traditional reference system. I.e., the relative performance of the traditional reference system is always 100%, both for the combi tank system and the preheating system. The performance of the reference systems are specially marked.

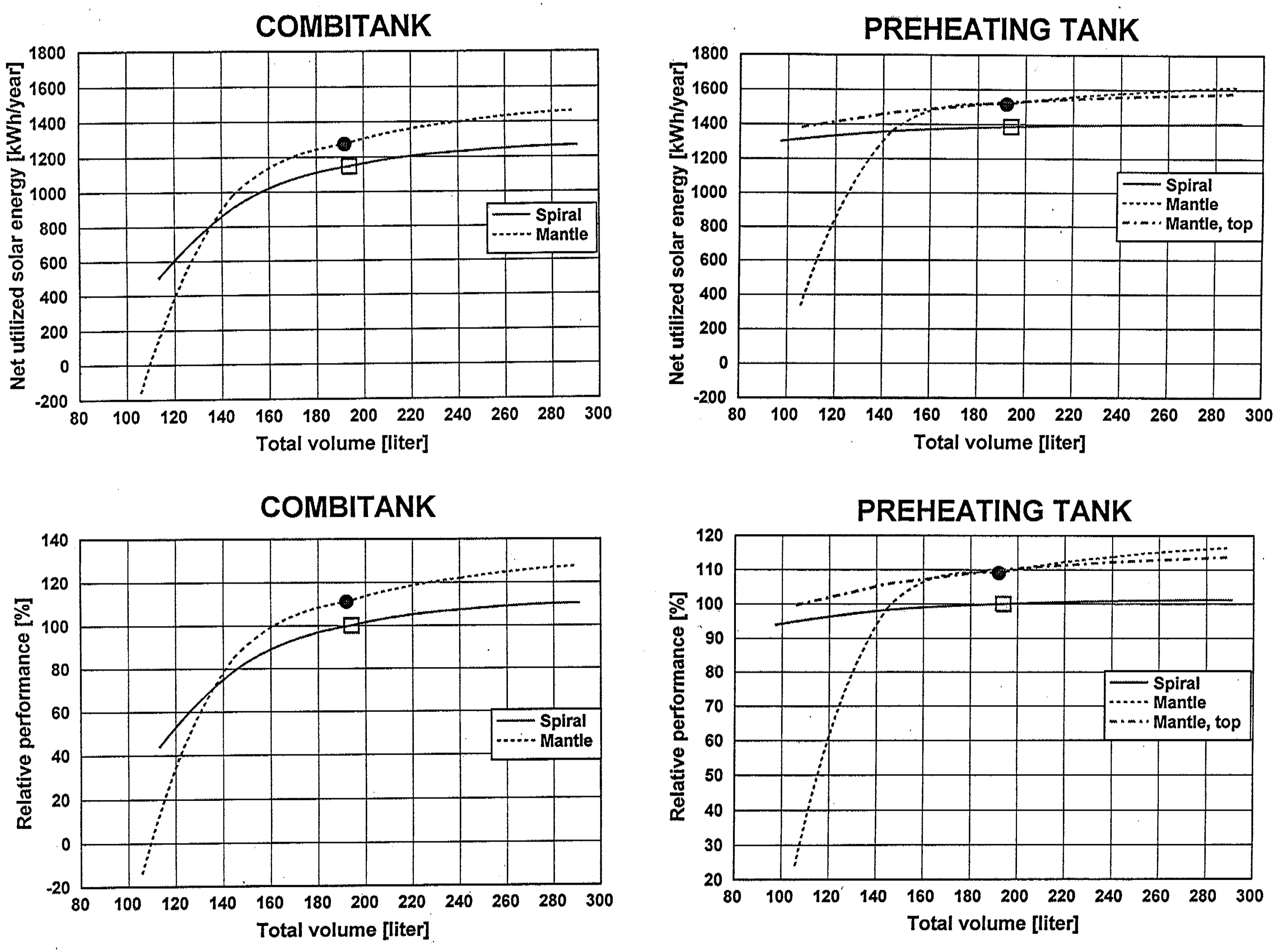


Figure 17. Thermal performances as a function of the tank volume.

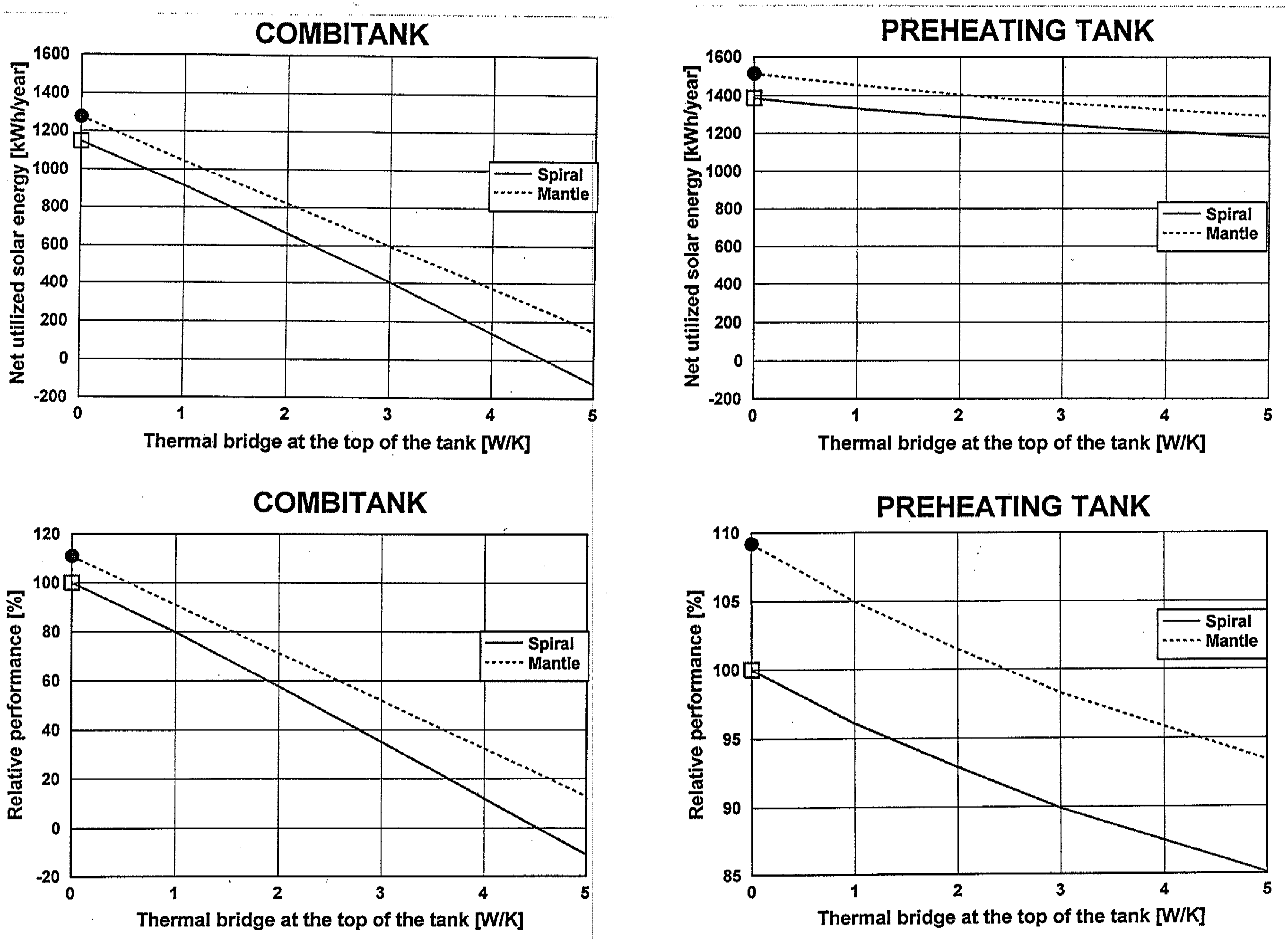


Figure 18. Thermal performances as a function of the thermal bridge in the top of the tank.

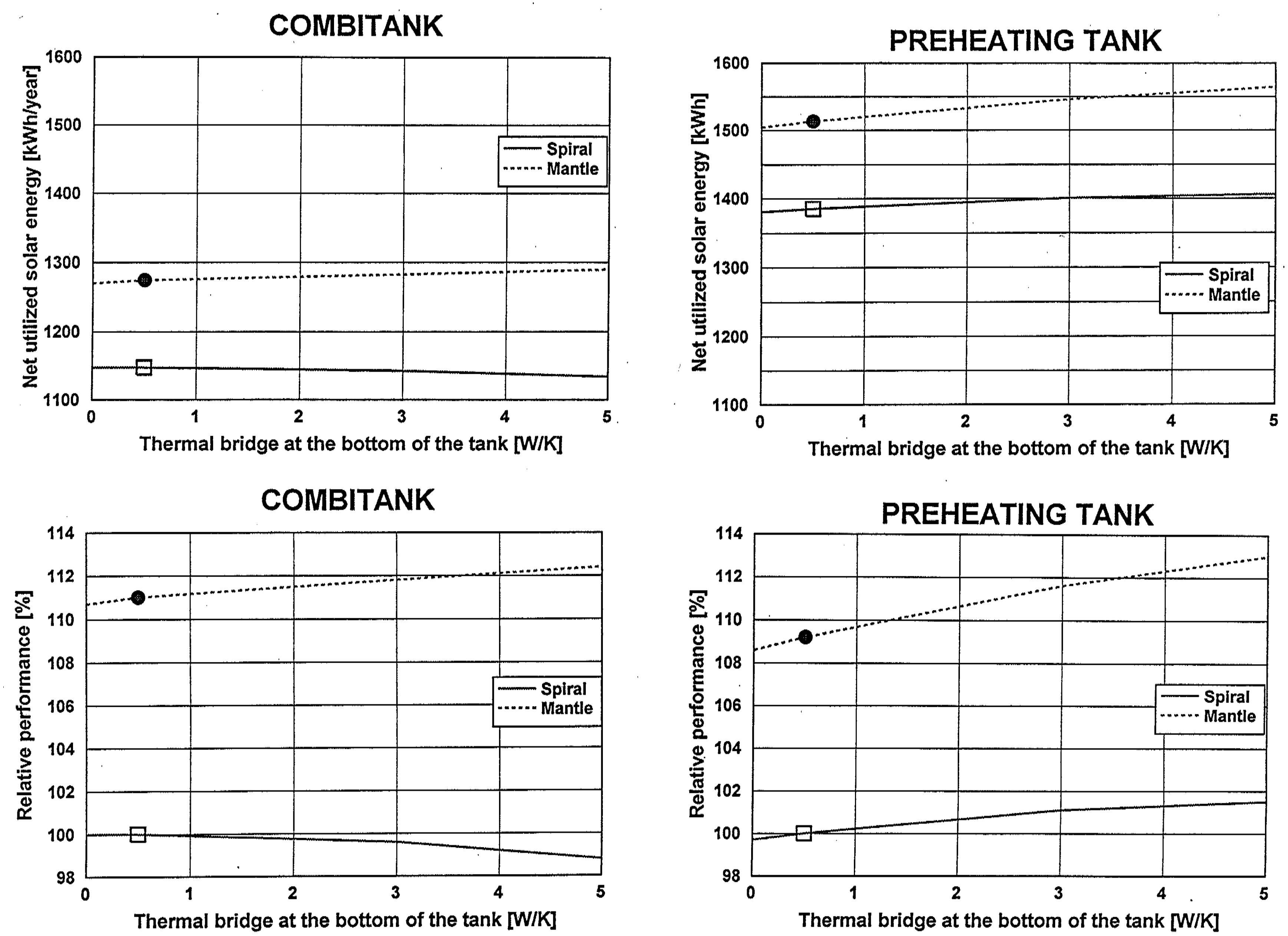


Figure 19. Thermal performances as a function of the thermal bridge in the bottom of the tank.

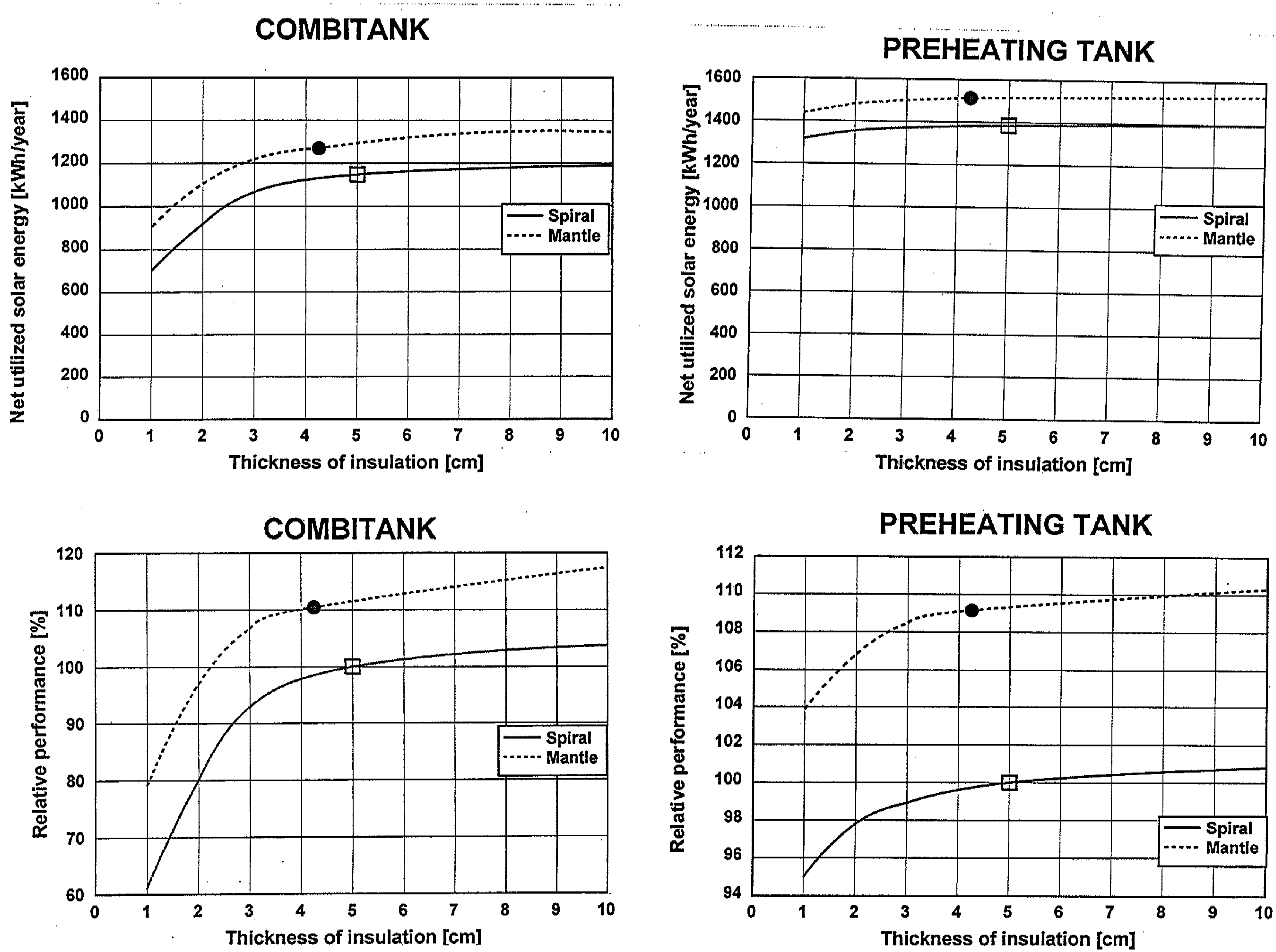


Figure 20. Thermal performances as a function of the insulation thickness of the tank.

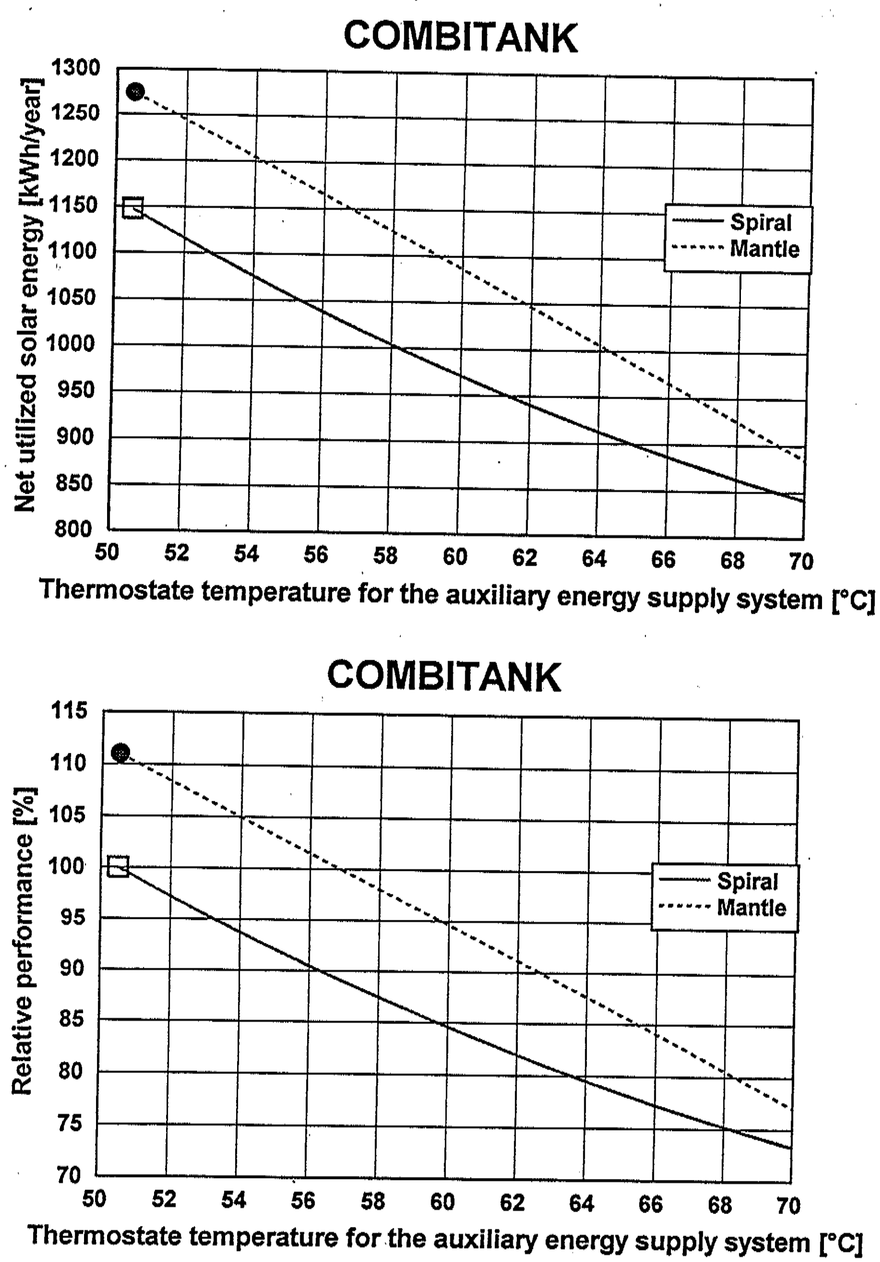
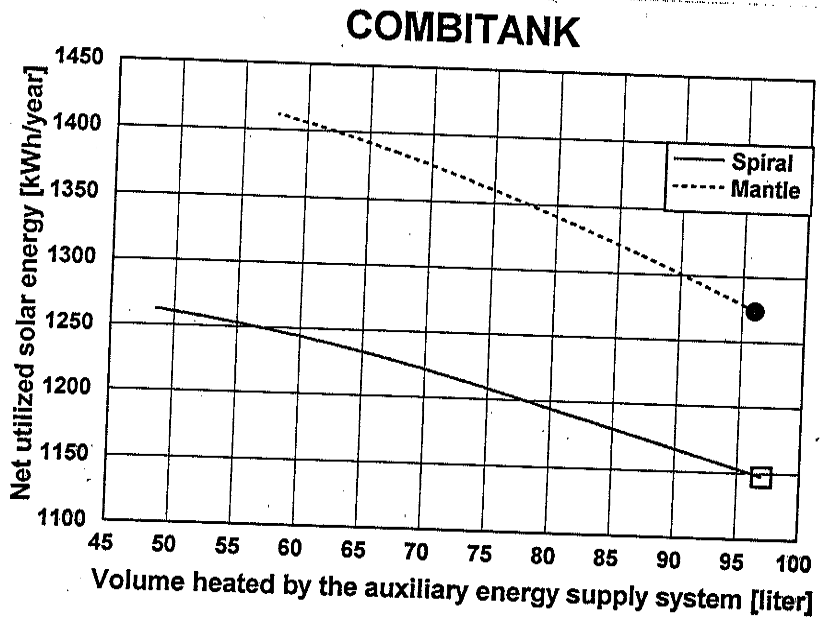


Figure 21. Thermal performances as a function of the thermostat temperature of the auxiliary energy supply system.



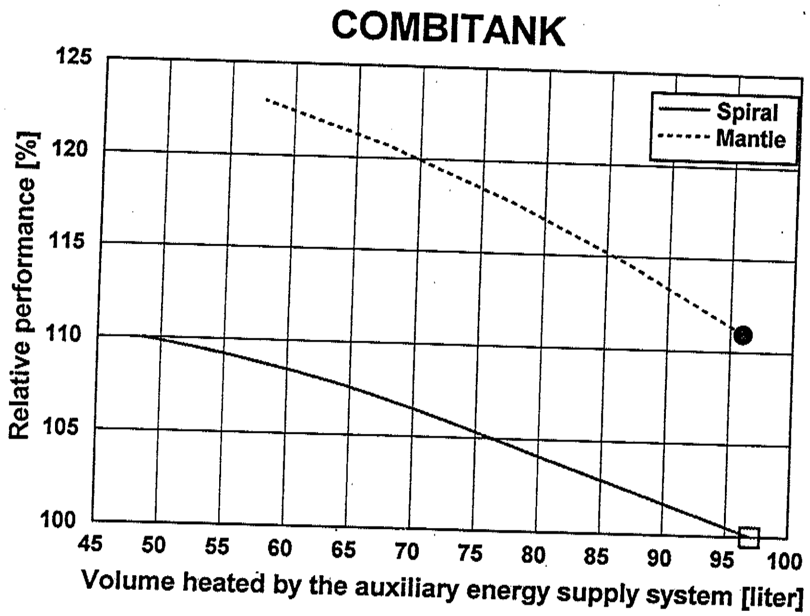
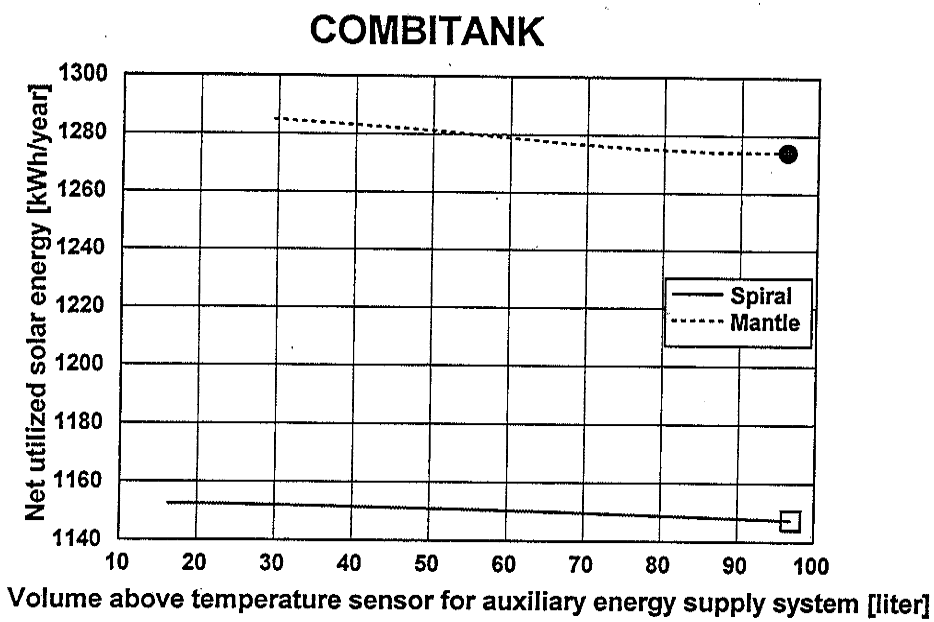


Figure 22. Thermal performances as a function of the water volume heated by the auxiliary energy supply system.



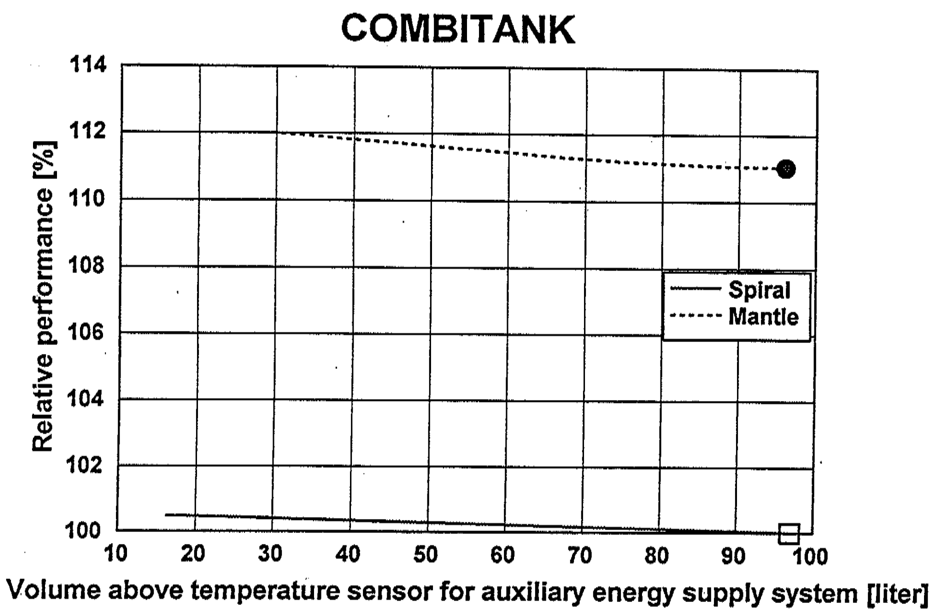


Figure 23. Thermal performances as a function of the water volume over the temperature sensor of the auxiliary energy supply system.

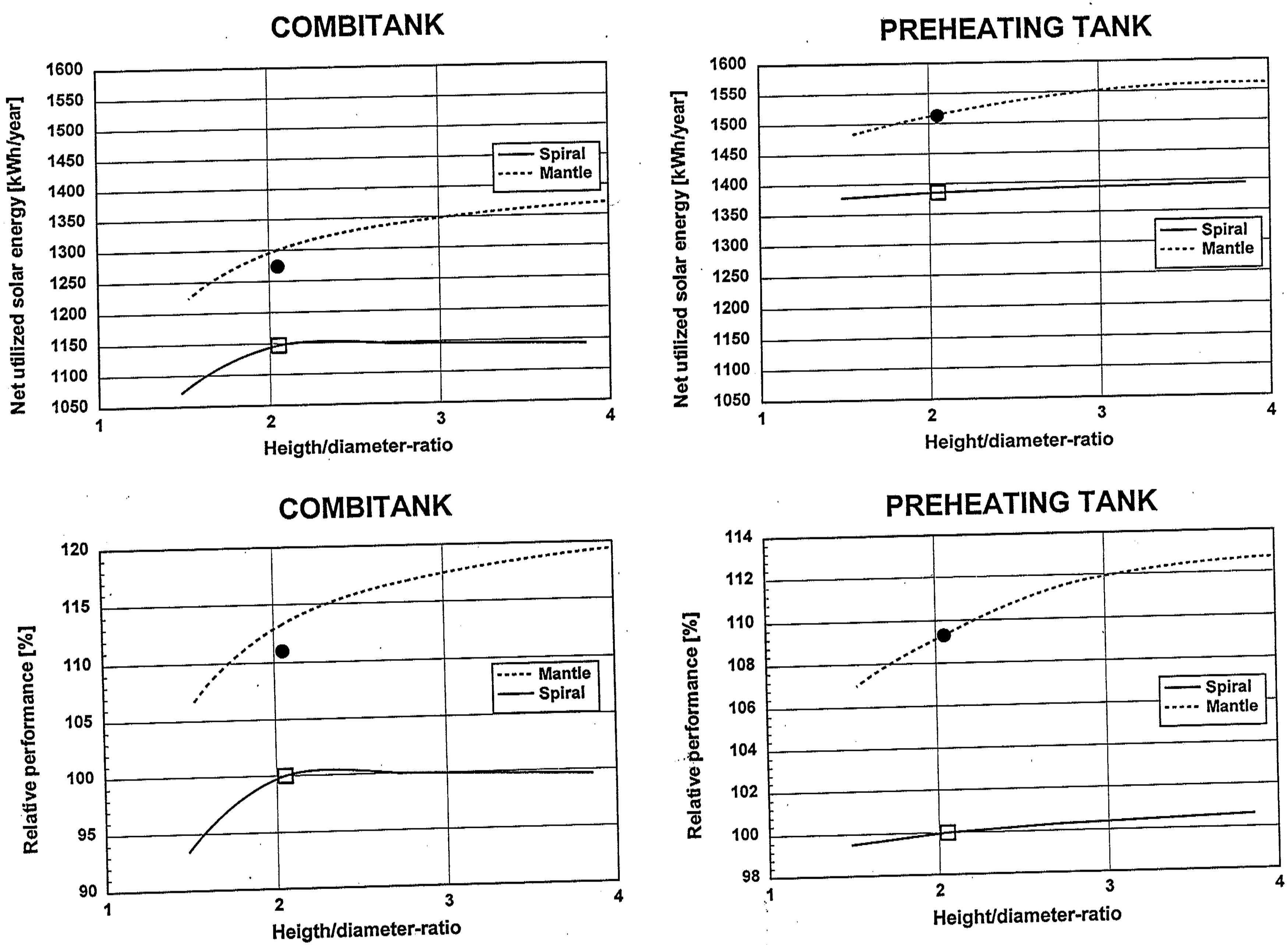


Figure 24. Thermal performances as a function of the height/diameter ratio of the tank.

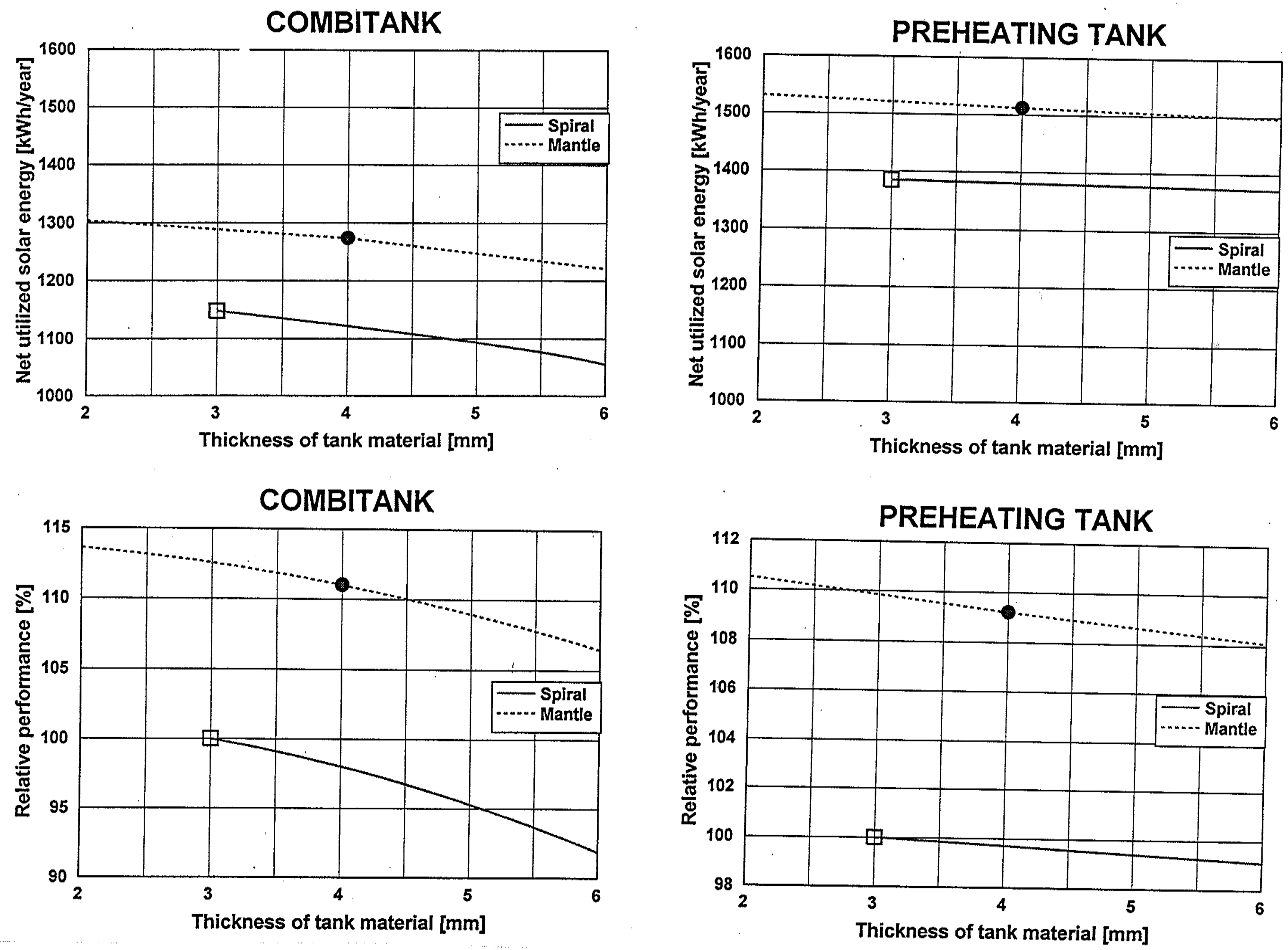


Figure 25. Thermal performances as a function of the thickness of the tank wall.

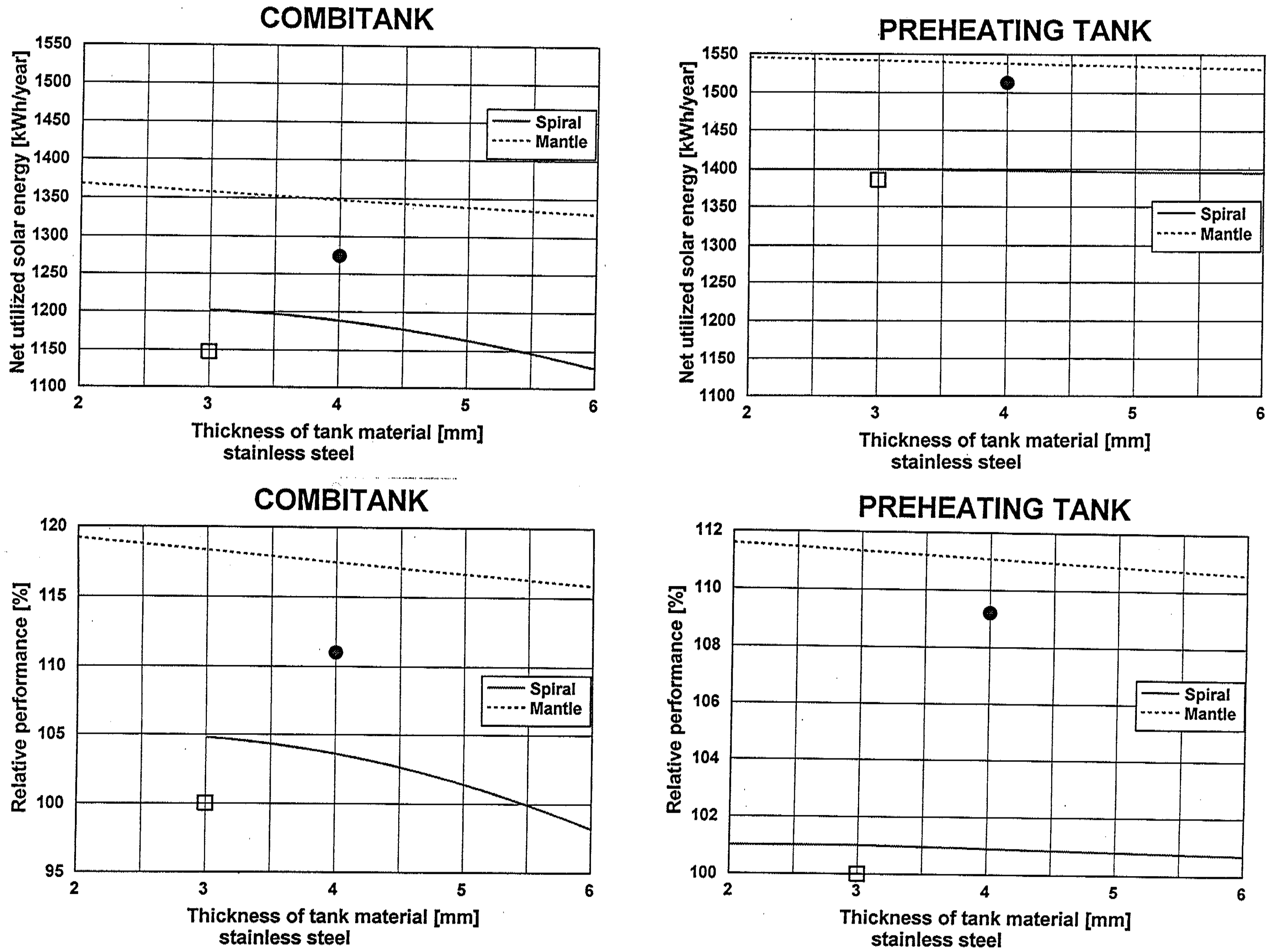


Figure 26. Thermal performances as a function of the thickness of the tank wall, which is made of stainless steel.

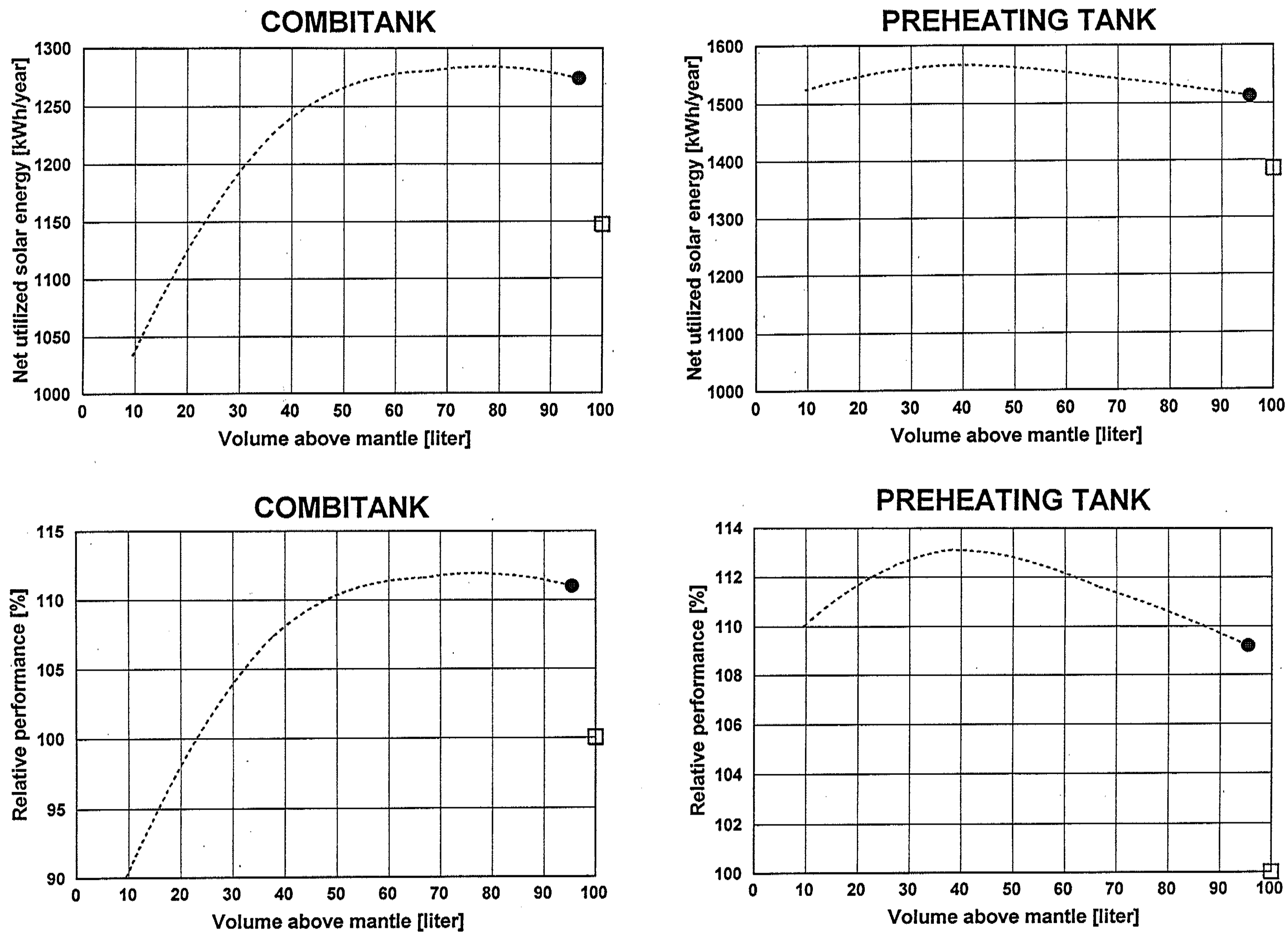


Figure 27. Thermal performances as a function of the water volume over the mantle.

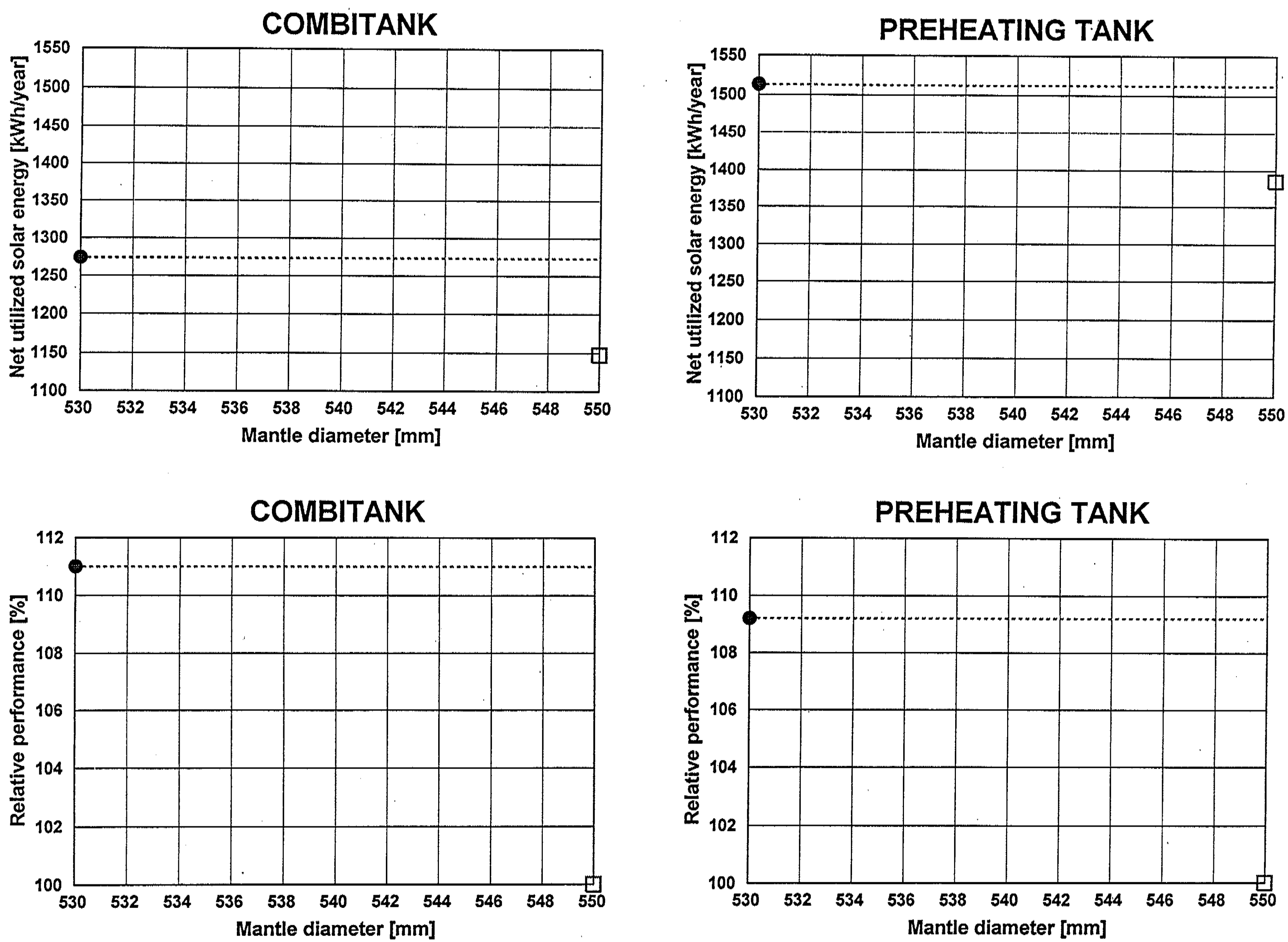


Figure 28. Thermal performances as a function of the mantle diameter.

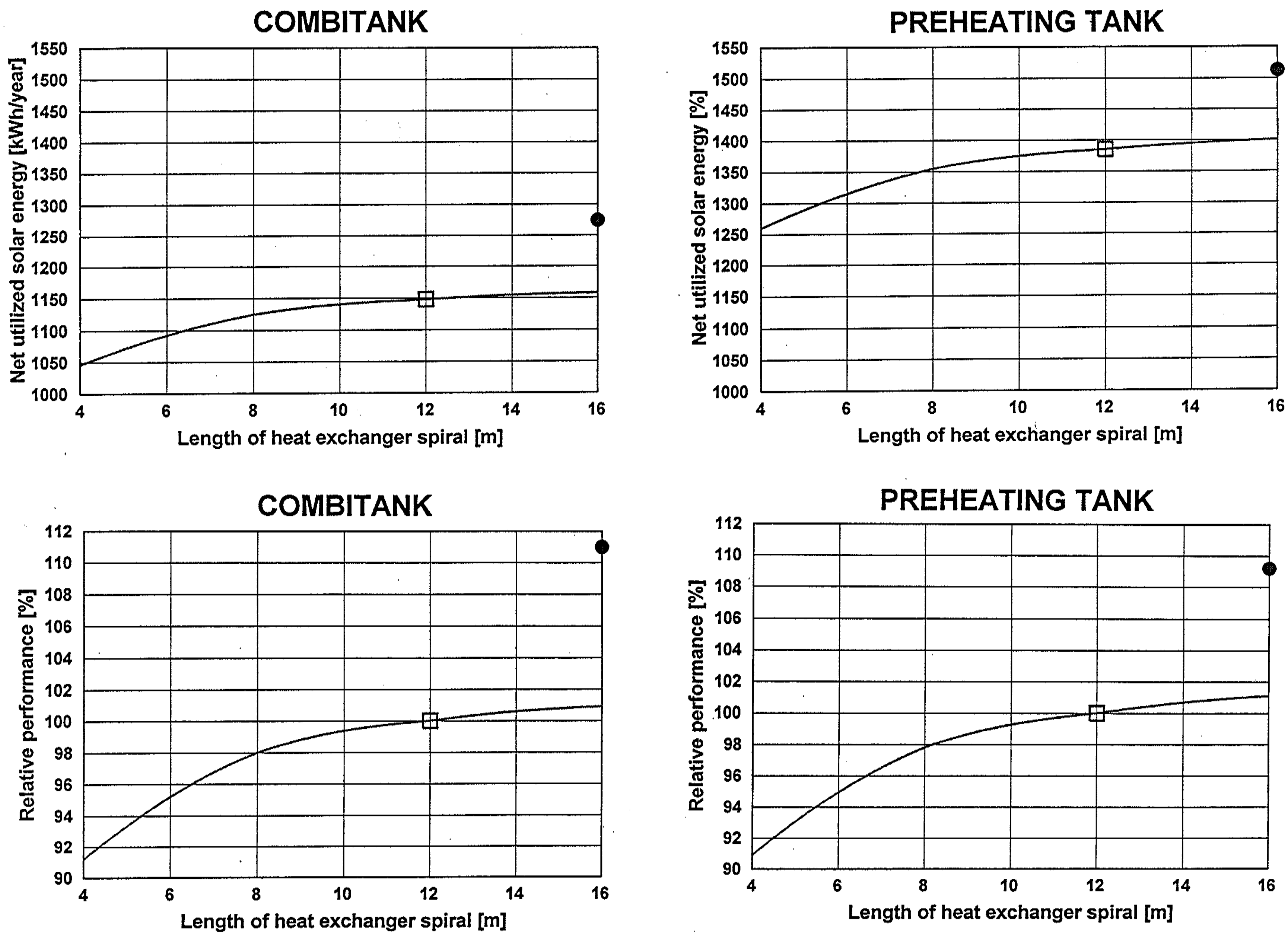


Figure 29. Thermal performances as a function of the length of the solar heat exchanger spiral.

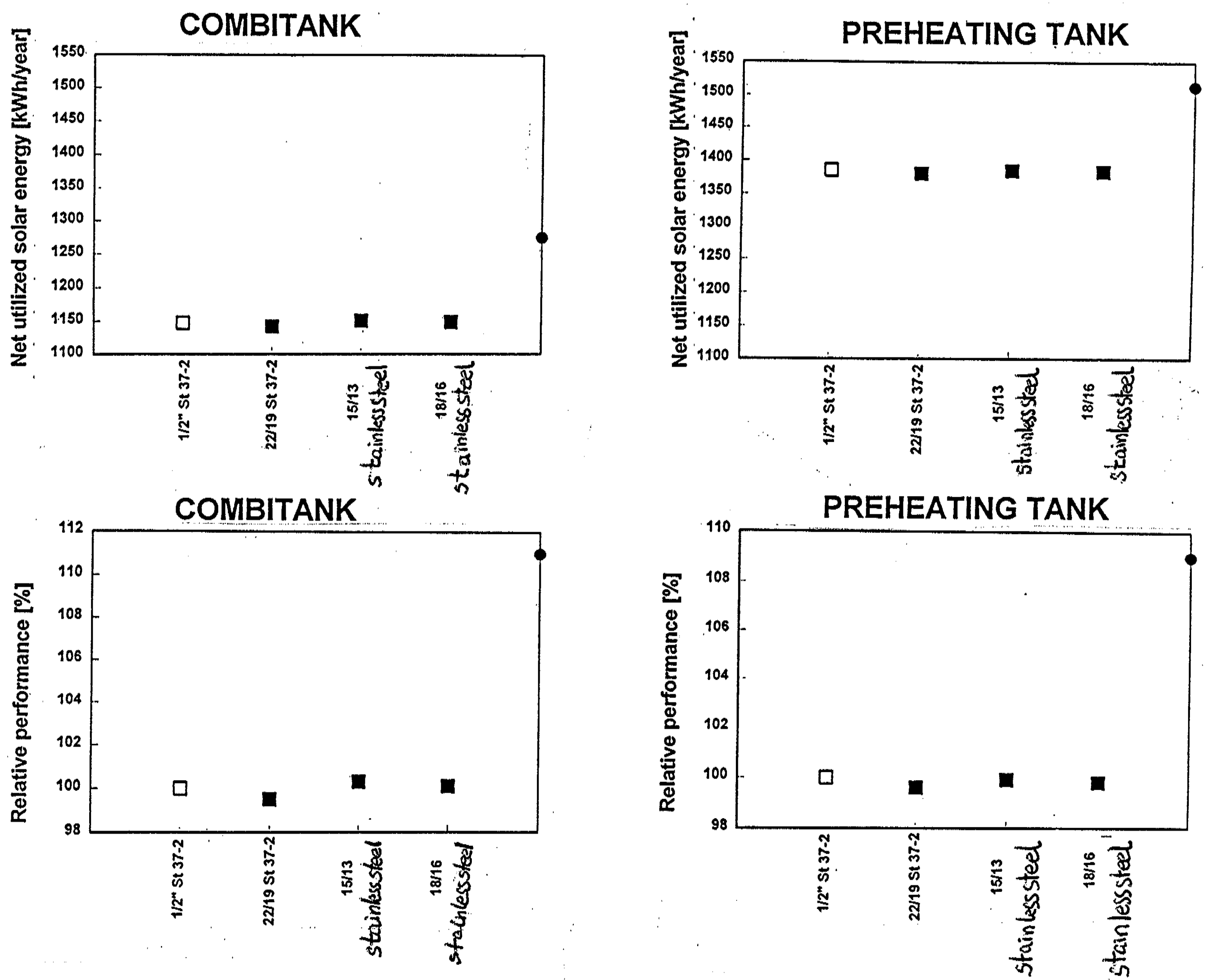


Figure 30. Thermal performances as a function of the solar heat exchanger spiral.

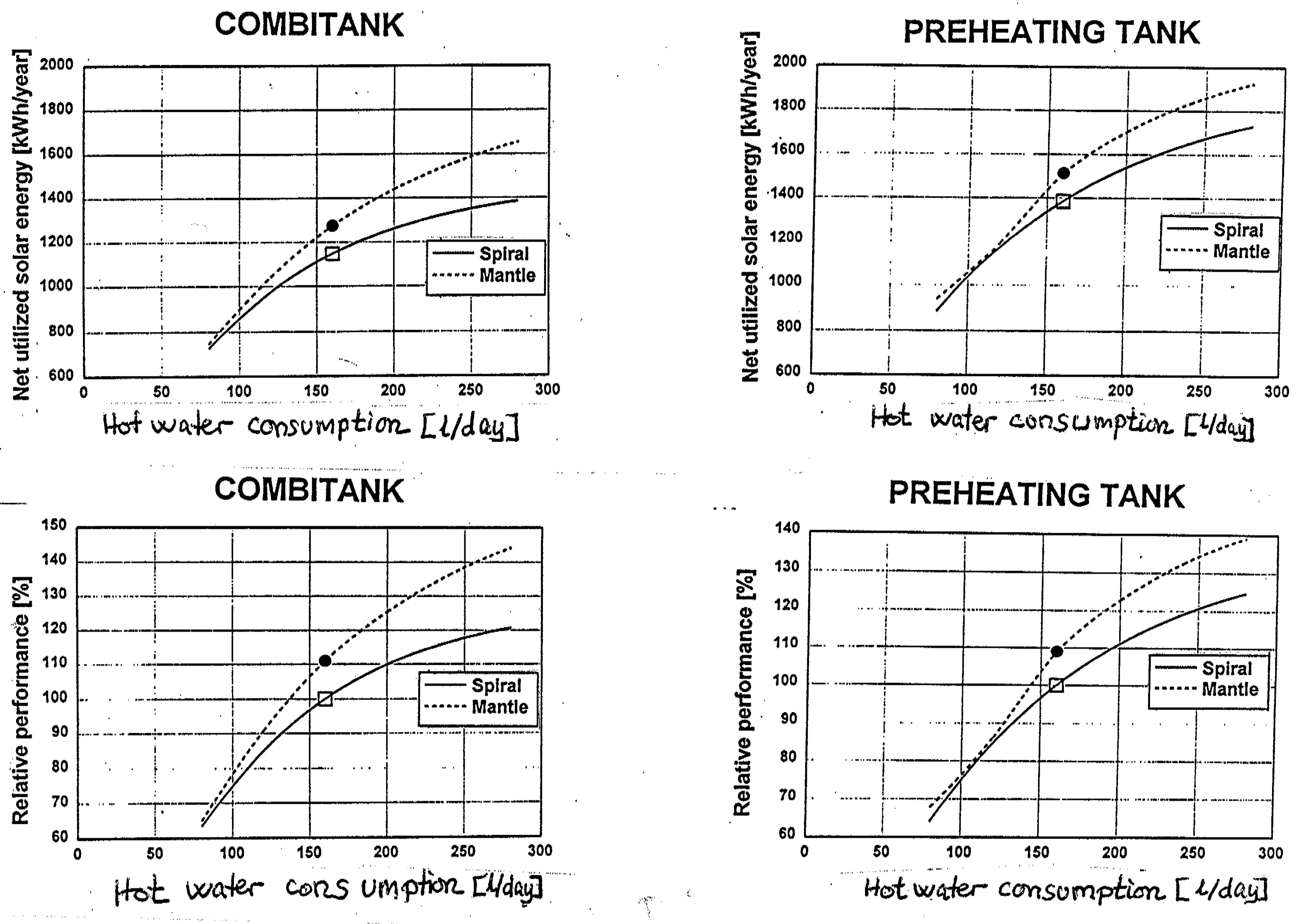


Figure 31. Thermal performances as a function of the hot-water consumption.

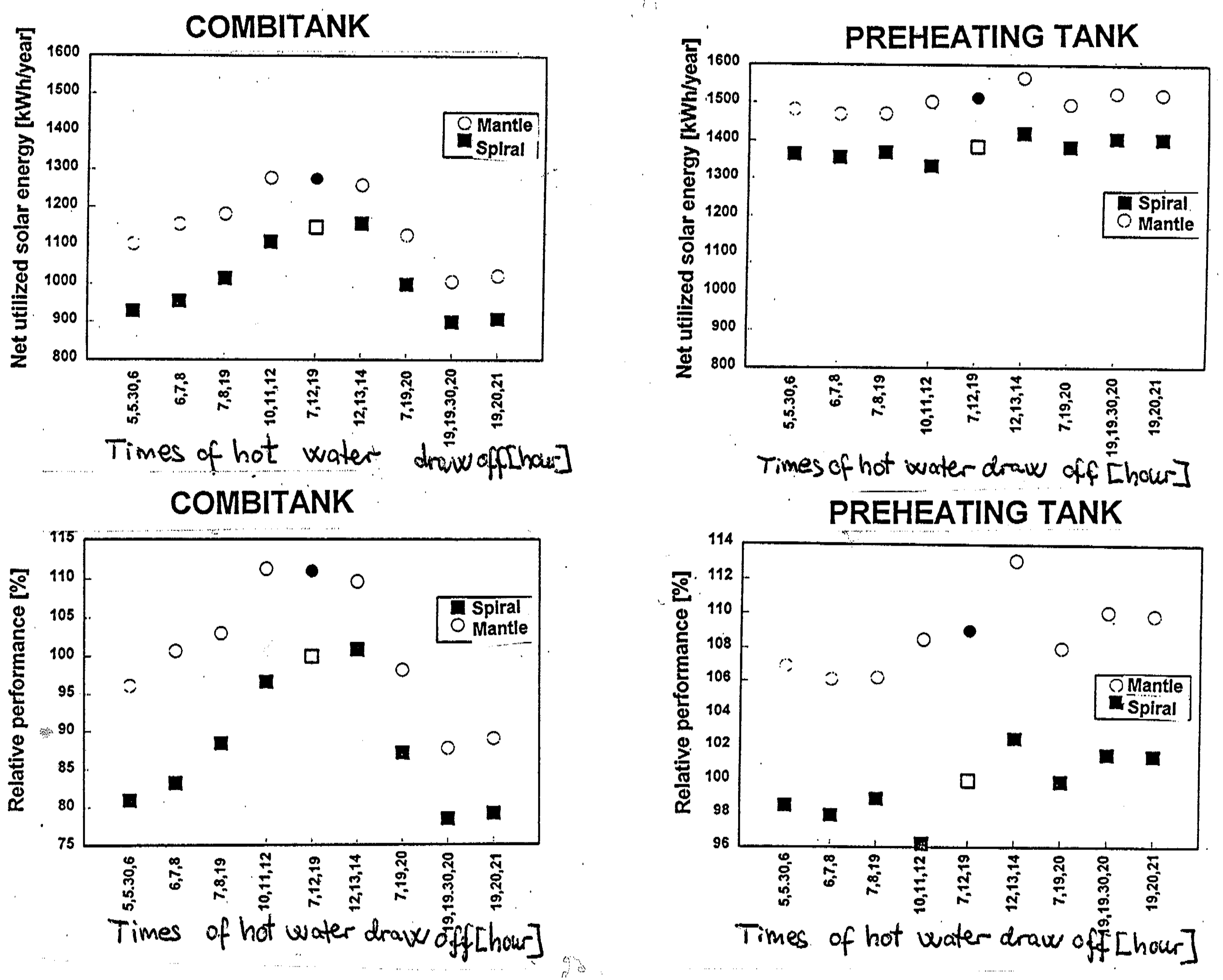


Figure 32. Thermal performances as a function of the draw off pattern.

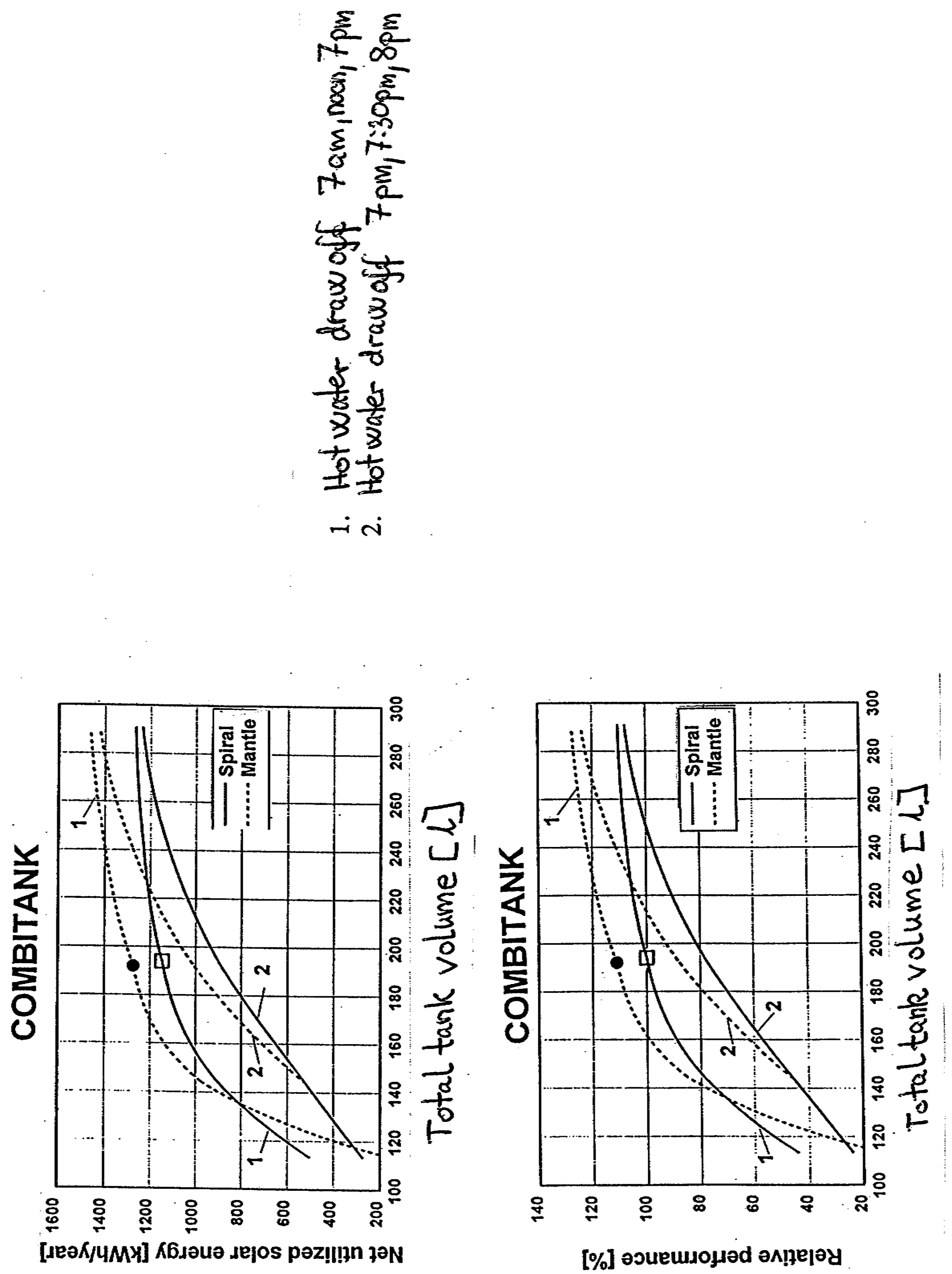


Figure 33. Thermal performances as a function of the tank volume and the draw off pattern.

Figure 17 shows the thermal performance as a function of the volume of the hot water tanks. The thermal performance of the preheating system is shown for two different mantle tanks: A mantle tank where the upper 96 l of the tank are not surrounded by the mantle, and a mantle tank where the tank is covered by the mantle from the top to the bottom. The larger the tank volume, the larger is the thermal performance. The thermal performance of the combi tank system is increased by about 10-15% if the volume is increased from 200 l to 300 l, whereas the performance is reduced by about 11% if the volume is reduced from 200 l to 160 l. The performance of preheating systems is not nearly so greatly affected by the volume of the tank. I.e., the volume of the pre-heater can be considerably smaller than the volume of the combi tank.

The performance of mantle tank systems is especially greatly reduced when the tank volume is reduced if the mantle does not surround the upper 96 l of the mantle. The reason for this is first and foremost that the heat transfer area of the mantle, and with that the heat exchange capacity rate from the solar collector fluid to the domestic water, is reduced particularly heavily when the tank volume is reduced.

Figure 18 shows the thermal performance as a function of the quantity of the thermal bridge placed at the top of the tank. For combi tank systems, the performance is reduced particularly heavily even for relatively small thermal bridges. For preheating systems, the performance reduction caused by such a thermal bridge is large, too, but less striking, however. Figure 19 shows that the thermal performance is not affected crucially by thermal bridges placed at the bottom of the tank. It is therefore strongly recommend that the insulation of the top of the tank should be performed entirely without thermal bridges. E.g., pipes ought not to be led through insulation to the top of the tank.

Figure 20 shows that the thermal performance is increased when the insulation thickness is increased. Here too, the variations of the thermal performance are far greater for the combi tank system than for the preheating system. I.e., the pre-heater does not need the same insulation thickness as the combi tank.

Figures 21, 22 and 23 show only the conditions for the auxiliary energy supply system for combi tank systems. The thermal performance is strongly reduced if the auxiliary set-point temperature is increased. The thermal performance is greatly increased if the volume heated by the auxiliary energy supply system is reduced. Finally, the thermal performance is not affected considerably by the placement of the temperature sensor controlling the heat transfer from the auxiliary energy supply system. In this connection, it should be mentioned that it is assumed in the calculations that the auxiliary energy supply system heats the whole top of the tank to the same temperature level. The placement of the temperature sensor is important if the auxiliary energy supply system creates thermal stratification in the top of the tank, e.g. when the auxiliary heat exchanger has a vertical height. On the basis of the calculations it can be concluded that it is extremely important that the auxiliary energy supply system only heats the water volume necessary for comfort reasons and that the water is not heated to a higher temperature level than necessary.

Figure 24 shows that the height/diameter ratio for mantle tanks should be as large as practicably possible, whereas the height/diameter ratio for spiral tanks should be about 2.

Figures 25 and 26 show that the performance is somewhat increased when the thickness of the tanks are reduced, and when stainless steel is used as tank material instead of steel St 37-2.

Figure 27 shows that for the combi tank the mantle should start on a level with the lowest part of the water volume that is heated by the auxiliary energy supply system. For preheaters the area of the mantle should be larger than for combi tanks.

Figure 28 shows that the thickness of the mantle has no influence worth mentioning on the thermal performance of the system. It should be mentioned, however, that the calculation model presupposes the same heat transfer conditions for the mantle irrespective of the size of the mantle thickness. These results must therefore be subject to certain reservations.

Figure 29 shows that the longer the solar heat exchanger spiral, the larger is the thermal performance of the traditional systems. The length of the heat exchanger spiral should be about 2 m per m^2 solar collector.

Figure 30 shows that the choice of diameter and material for the solar heat exchanger spiral has no influence worth mentioning on the performance of the traditional systems.

Figure 31 shows that the larger the hot-water consumption, the lager is the thermal performance. The larger the hot-water consumption, the larger the increase in the extra thermal performance of the mantle tank system, and the smaller the solar fraction.

Figure 32 shows how the draw off pattern influences the thermal performance. In these calculations, 53.33 l of hot water are tapped from the tank three times a day. The thermal performance of the combi tank system is greatly influenced by the draw off pattern. The thermal performance is largest if water is only tapped in the middle of the day, whereas the performance is smallest if water is only tapped in the evening. The performance is, for instance, reduced by more than 20% if the whole hot-water consumption takes place in the evening. It appears that the increase in performance for mantle tank systems is particularly large if all the hot water is tapped in the morning.

The draw off pattern has some effect on the thermal performance of preheaters, too. For preheaters the thermal performance is largest if all the hot-water consumption takes place in the afternoon or in the evening.

For combi tank systems, figure 33 shows the performance as a function of the tank volume for two different draw off patterns. It appears that if the draw off pattern is "unequal", i.e. if water is only tapped in the evening, there is a need for a larger tank volume than if the draw off pattern is "normal".

The importance of the design of the heat-transfer system for the auxiliary energy supply system has not been illuminated by means of performance calculations. In [13] rules of thumb have been laid down for the design of heat exchanger spirals of hot water tanks that are connected to boilers. It is stated that the heat exchanger spiral should be placed in the top of the tank, that the volume flow rate through the spiral must be large, typically about 10 l/min., and that the heat exchange capacity rate for the heat exchanger spiral should be larger than the boiler power/22.

By means of the developed theory in [6], the heat exchange capacity rate of four heat exchanger spirals is calculated for different operation conditions and spiral lengths. All the calculations have been carried out with a volume flow rate through the spiral of 10 l/min. Figures 34 and 35 show examples of calculated heat exchange capacity rates at a storage temperature of 45°C. The larger the pipe diameter and the larger the power supply, the greater the heat exchange capacity rate.

From these rule of thumbs, these calculation results have been used for determining the recommended length of the heat exchanger spiral in the top of a solar tank. Figure 36 show the recommended lengths for heat exchanger spirals in the top of the solar tank as a function of the boiler power. The larger the boiler power, the longer the recommended spiral. The smaller the pipe diameter for the spiral, the longer the recommended spiral.

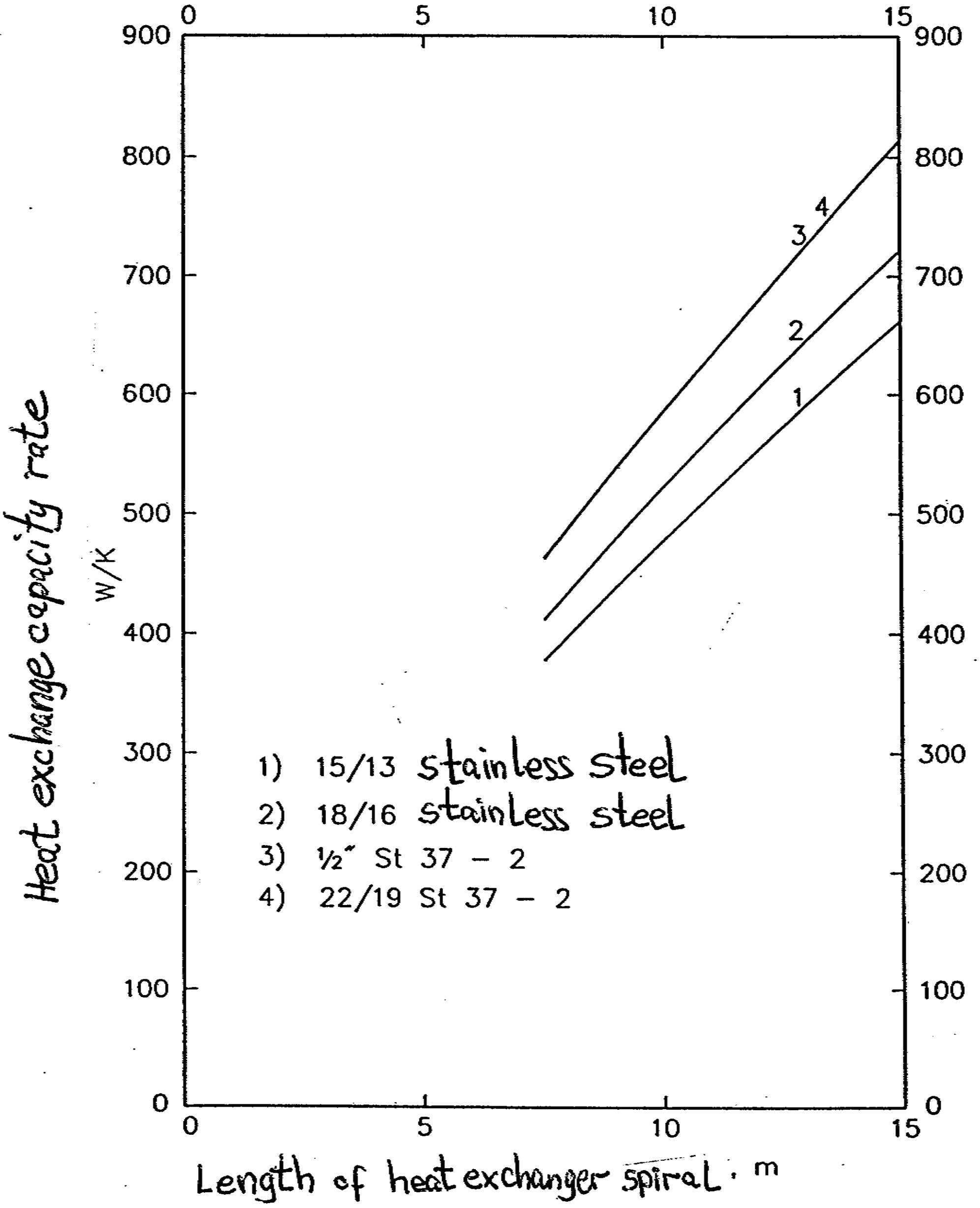


Figure 34. The heat exchange capacity rate of different heat exchanger spirals as a function of the length of the heat exchanger spiral at a volume flow rate through the spiral of 10 l/min., a hot water tank temperature of 45°C and power supply of 15 kW.

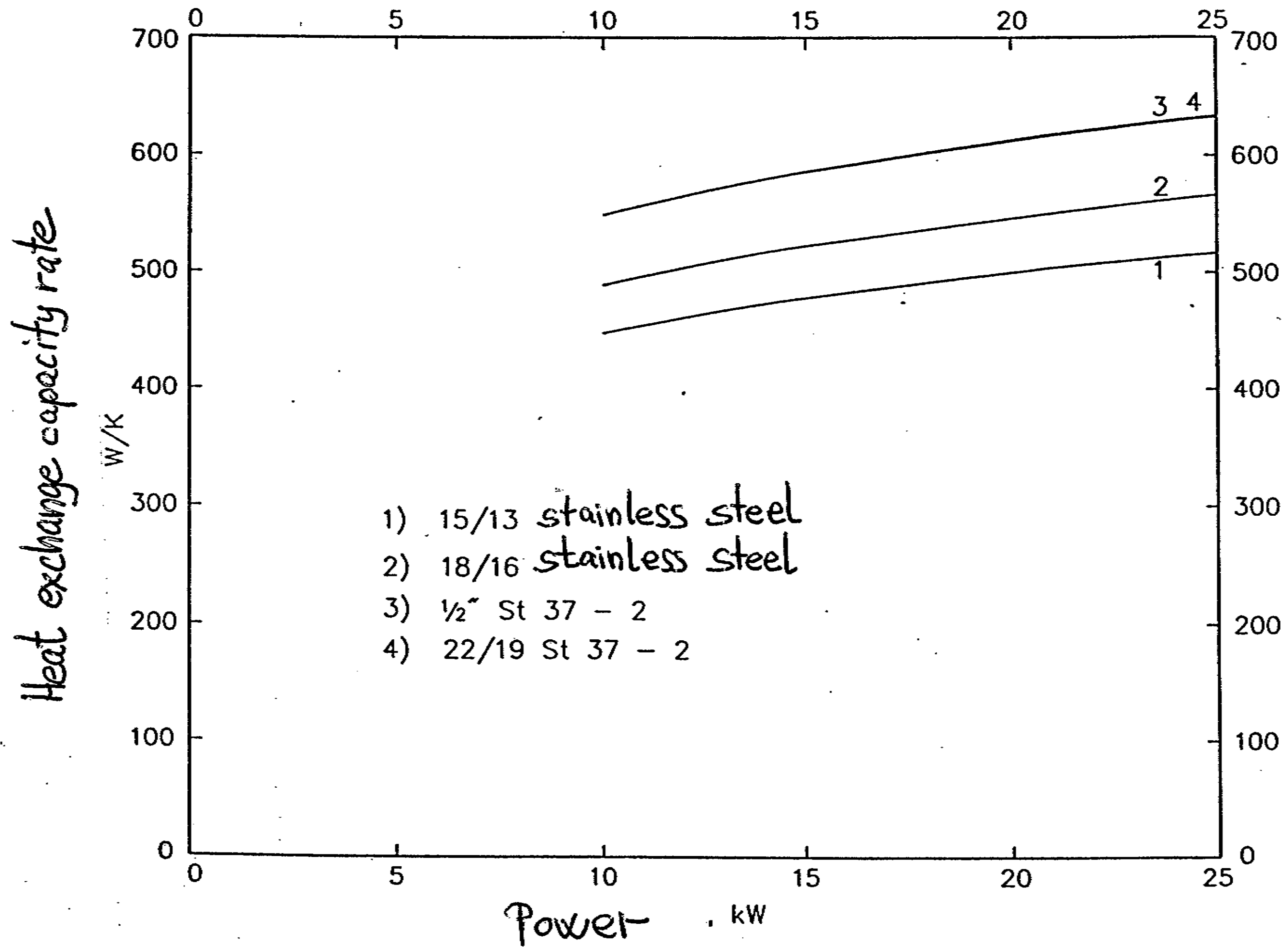


Figure 35. The heat exchange capacity rate of different 10 m long heat exchanger spirals as a function of the power supply at a volume flow rate through the spiral of 10 l/min. and a hot water tank temperature of 45°C.

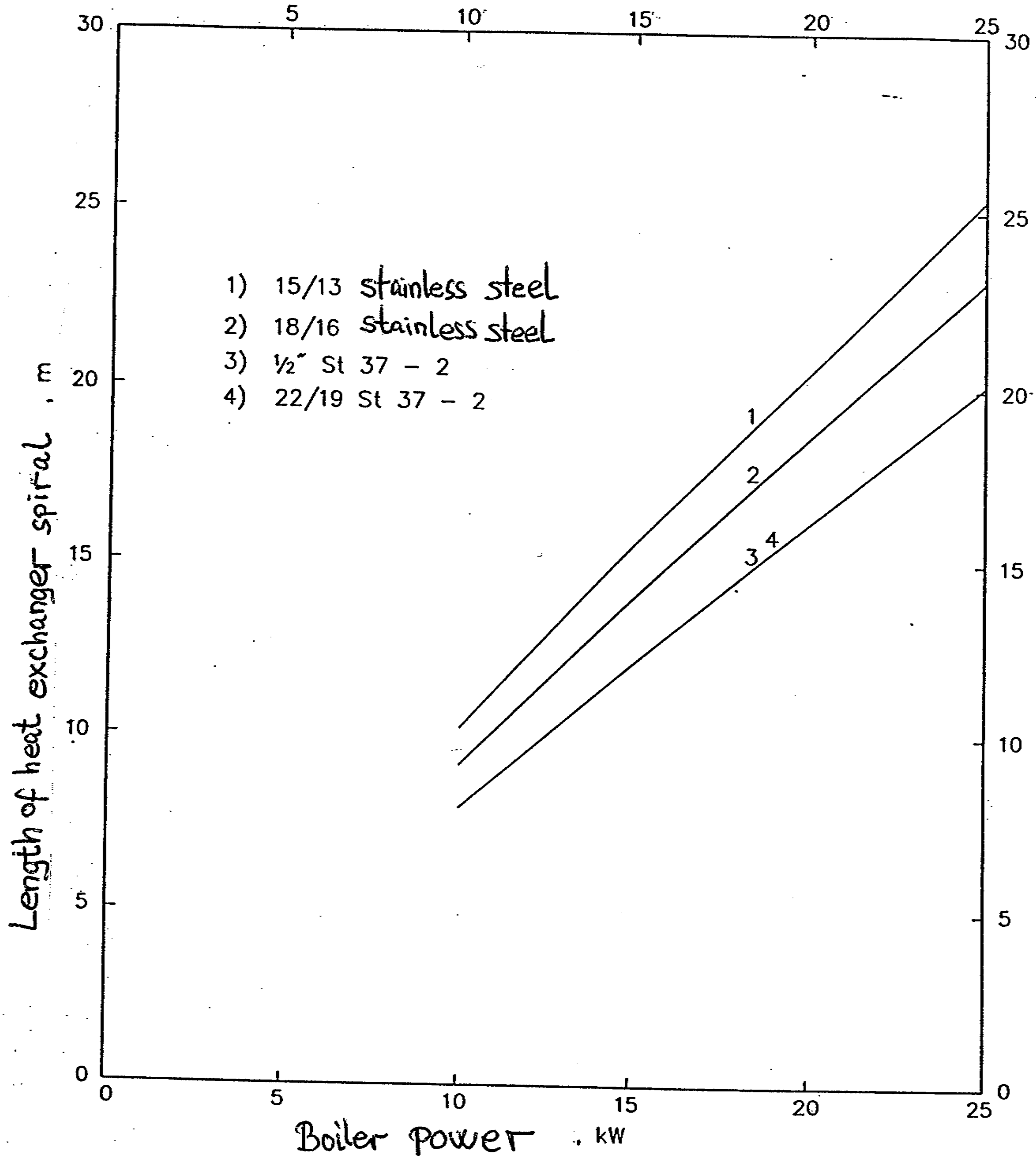


Figure 36. Recommended lengths for heat exchanger spirals in the top of the tank as a function of the boiler power.

4. GUIDELINES FOR DESIGN OF HOT WATER TANKS

The hot water tanks taken into calculation in paragraph 3.2 are traditionally designed hot water tanks. These tanks are by and large designed as the hot water tanks marketed today. Without problems, the tanks can be produced relatively cheaply in large numbers by the tank manufacturers.

Storage tanks can also be designed unconventionally. The aim will then typically be to reduce the price of the heat storage. A series of preliminary investigations concerning inexpensive hot water tanks have been carried out [14], [15], [16]. These hot water systems are based on a small cheap standard hot water tank and an external heat exchanger, which is possibly installed in a cheap pressureless tank. There is a need for development work before such tanks can be introduced on the market. Furthermore, investigations have shown that a hot water tank consisting of a standard tank and an external heat exchanger performs worse than a mantle tank [17]. It is outside the framework of this project to evaluate such unconventionally designed tanks.

The calculation results from paragraph 3.2 and a number of conditions that have not been taken into calculation form the basis of how traditional hot water tanks should be designed. In paragraph 4.1, a number of important conditions for hot water tanks are mentioned, and paragraph 4.2 lays down guidelines for the design of hot water tanks.

4.1 Design of hot water tank – important conditions

Tank type

From a performance point of view, the best hot water tank is a vertical cylindrical tank. Well-designed low flow systems with mantle tanks can, all things being equal, perform up to 20% more than traditional spiral tank systems with high volume flow rates in the solar collector loops. Even for high volume flow rates in the solar collector loops the thermal performance of mantle tank systems is higher than the thermal performance of spiral tank systems.

Inlet

The greater the thermal stratification in a hot water tank during typical operation, the greater the thermal performance of the solar heating system.

The thermal performance of a solar heating system with a fully mixed hot water tank can be about 2-3 times smaller than the performance of a solar heating system with a heat hot water tank with the greatest possible thermal stratification. I.e., it is very important that the thermal stratification in hot water tanks, to the greatest extent possible, is built up both when the solar collector is in operation and during draw-offs. Further, the thermal stratification must be retained to the greatest extent possible in periods when the solar collector is not in operation and during periods without draw-offs.

Investigations have shown that water supplied to hot water tanks can create mixing that spoils the thermal stratification in the tanks. It is therefore of vital importance that all inlets to tanks are designed in a way that this mixing becomes smallest possible. The water ought to be led horizontally into the tank at as low a flow rate as possible. For small tanks, this fact should be noticed if the system is equipped with a circulation pipe. It is important that the return water from a circulation pipe does not create mixing in the tank.

In [18] it has been investigated how the mixing is affected by different inlet designs and volume flows. The investigations included five different inlet designs, see Figure 37. All the inlets were placed in the vertical wall of the tank.

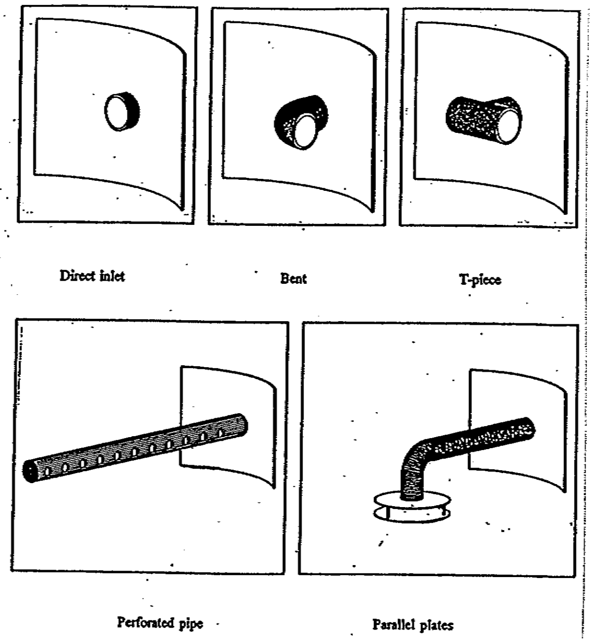


Figure 37 The investigated inlet designs.

The investigations showed that the parallel plates caused least mixing, the T-piece is the second best inlet design followed by the perforated pipe and the direct inlet. The elbow is the poorest inlet design. Even at small volume flow rates for water entering the tank, mixing is created when this inlet is used.

The cold water is often supplied to the tank through the tank bottom. E.g. through the holes on the sides of a small vertical plastic pipe, which is closed at the top. Another inlet design for the cold water consists of a vertical direct inlet combined with a baffle plate. Both of these inlet designs can function fine without very much mixing being created.

Thermal bridges and pipe connections

Experience has shown that the heat loss of solar tanks is strongly influenced by the location of thermal bridges and the auxiliary equipment of the solar heating system [5]. If a thermal bridge is placed in the bottom of the tank, the water at the thermal bridge is cooled relatively rapidly and if the solar collector is not in operation, it forms a cold stagnant insulating layer above the thermal bridge so that the heat loss from the thermal bridge becomes relatively small. If a thermal bridge is placed in the top of the tank, the thermal bridge will remain hot, as the water cooled by the thermal bridge is replaced by hotter water from the storage because of density differences. I.e., natural convection in the storage keeps the temperature of the thermal bridge high, and the heat loss from the thermal bridge therefore becomes large. Similar considerations can be applied concerning the heat loss from the auxiliary equipment. The auxiliary equipment is most appropriately placed under the tank in an insulated instrument room. Such a position limits the heat loss of the equipment and the storage as much as possible.

The pipe connection also has relevance to the heat loss from the heat storage. A pipe connection through the insulation is the type of thermal bridge that can cause the largest heat loss because internal fluid circulation can occur in the pipe, as the density of the fluid is temperature dependent. This internal fluid circulation will heat large or small parts of the pipe system resulting in large or small storage heat loss. It is therefore important that the pipe connection is **never** placed in the top of the storage, that the pipes are well insulated, and that the pipes are downwards from the tank, so that internal circulation in the pipe system is prevented.

Furthermore, during operation large temperature differences often occur between the hot water of the tank top and the cold water of the tank bottom. If this is considered along with the above-mentioned conditions, all heat loss conditions indicate that 1) the top of the storage must be well insulated without any form of thermal bridges, 2) all thermal bridges, e.g. pipe connections, tank fastenings etc., must be placed in the bottom of the storage, and 3) all auxiliary equipment must be placed in an insulated instrument room under the storage tank.

It must be recommended, for instance, that the domestic hot water is tapped from the top of the hot water tank through a plastic pipe, stretching through the tank from top to bottom.

If necessary, the hot water from the top of the tank can be led out through the upper part of the wall and from here further downwards in a pipe situated in the tank insulation.

Systems with circulation pipe

For systems equipped with a circulation pipe, however, the hot water should not be tapped through a vertical pipe, but led **direct** to the circulation pipe from the top of the tank.

Investigations have shown that if solar heating systems are equipped with a circulation pipe, systems, in which the hot water is led **direct** to the circulation pipe from the top of the tank, perform about 15-20% more than systems where the hot water is led to the circulation pipe through a vertical plastic pipe, [19], [20], [21].

The reason for the small thermal performance of solar heating systems using the vertical pipe is that the advantageous thermal stratification of the tank is destroyed as heat is transported downwards in the tank with the circulating water. The investigations showed that for hot water tanks equipped with a circulation pipe it is recommended:

- to draw the hot water **direct** from the top of the tank.
- to be careful with the insulation to reduce the heat loss caused by the pipe connection in the top of the tank as much as possible. A good solution is to place the pipe along the side of the tank inside the tank insulation.
- to equip the circulation pipe returning to the hot water tank with an automatic regulation valve that regulates the volume flow rate in the circulation pipe so that the return temperature from the circulation pipe is kept at a certain temperature in advance. In this way the volume flow rate in the circulation pipe does not become unnecessarily high so that the mixing in the tank is reduced as much as possible.
- to lead the water from the circulation pipe back to the top of the tank through the side of the tank.
- to control the pump of the circulation pipe so that flow in the pipe only occurs when necessary.

Heat exchanger spiral for the auxiliary energy supply system

In the top of hot water tanks normally a heat exchanger spiral is installed that is connected to the auxiliary energy supply system. To prevent that the thermal stratification in the hot water tanks is destroyed owing to the pipes to and from the heat exchanger spiral, the pipes should be led in through the side of the tank at the level where the heat exchanger spiral is placed. The pipes, which must be well insulated, must be led downwards from the tank in order to reduce the risk of internal circulation as much as possible.

Deposition of lime

Investigations have shown that about 2.5 times as much lime is deposited in spiral tanks for traditional solar heating systems as in mantle tanks for low flow systems, [11].

The reason why least lime is deposited in mantle tanks is partly that heat exchanger spirals are more compact than mantles, partly that the temperatures that are created in the top of the mantle tank are high. That is, the higher the temperature of the drawn water, the less water volume is drawn from the tank. Consequently, more water flows through the spiral tank of a traditional solar heating system than through the mantle tank of a low flow system. The larger water volume results in a larger deposition of lime.

Most of the lime is deposited in the bottom of the tank. So in mantle tanks the lime will have no effect on the heat exchange capacity rate. The heat exchanger spiral in a spiral tank is normally placed in the lower part of the tank. After a number of years the lime will therefore cover a greater or smaller part of the heat exchanger. At one time the heat exchange capacity rate and the thermal performance will therefore be appreciably reduced.

Further, due to the reduced heat exchange capacity rate, the solar collector fluid will boil in the collector resulting in increased maintenance costs and/or reduced durability of the solar heating system. Thus, the advantages by using mantle tanks are not only related to the increased thermal performance.

4.2 Design rules

Below design rules for hot water tanks are laid down, both for combi stores and for pre-heaters. In principle, hot water tanks prepared for solar heating should be designed according to the same guidelines as are the combi stores.

The design rules mentioned below are not sufficient to determine the design of hot water tanks. The installation and corrosion conditions for the tanks are also important. As an example, a saving in the production of a hot water tank can be lost as a result of a more difficult installation, or corrosion in the tank with subsequent renewal/repair. As mentioned, in [3] the installation and corrosion conditions for hot water tanks are described, including how the auxiliary equipment for solar heating systems is best designed and installed. Therefore, solely rules for the design of the tank are laid down here.

General

There must not be any thermal bridges in the top of the tank, e.g., pipe connections through the upper part of the insulation must be avoided.

Domestic cold water must be supplied in the bottom of the tank in order to avoid mixing.

The domestic hot water should be tapped from the top of the tank through a plastic pipe reaching through the tank from the top to the bottom. If necessary, the hot water from the top of the tank can be led out through the upper part of the wall and from this further downwards in a pipe situated in the tank insulation.

For hot water tanks in systems with a circulation pipe, the hot water should be tapped direct from the top of the tank. The water is led down along the side of the tank in a pipe within the tank insulation. The circulation outlet pipe should be provided with an automatic regulation valve that ensures that the return temperature is kept at a level set in advance. The water from the circulation pipe should be led back to the top of the tank through the side of the tank. Tanks for systems with and without a circulation pipe could possibly be identical except for the mentioned regulation valve. In that case it should be easy to block the vertical pipe that is not used.

COMBI STORE

The tank volume should be about 0.6-0.9 times the daily hot-water consumption plus the volume heated by the auxiliary energy supply system. The more "unequal" the consumption pattern, the larger the volume should be. E.g., if all the hot water is tapped in the evening, the volume should be about 0.9 times the daily consumption plus the volume heated by the auxiliary energy supply system. The tanks typically have a volume between 150 l and 300 l.

The insulation thickness should be about 3-4 cm if polyurethane foam is used. Extra insulation has the largest effect around the upper part of the tank.

The heat exchanger spiral for the auxiliary energy supply system is placed at the top of the tank. The length of the heat exchanger spiral, which should depend on the power of the boiler and the chosen pipe diameter, is determined by means of figure 36.

The auxiliary energy supply system only has to heat the water volume that is required for comfort reasons and not to a higher temperature than necessary. Normally, a volume of max 100 l is heated to 50°C.

The tank should be equipped with a thermostat that can break the flow through the heat exchanger when the temperature is sufficiently high.

The pipes to and from the heat exchanger spiral for the auxiliary energy supply system should be led in through the tank wall at the level where the heat exchanger spiral is placed. The pipes should be led down along the side of tank inside the tank insulation.

Mantle tank

The mantle should start on a level with the lowest part of the water volume that is heated by the auxiliary energy supply system(s). The mantle should end on a level with the bottom of the tank.

The height/diameter ratio should be as large as practically possible.

The temperature sensor of the control system of the solar heating system should be placed at the bottom of the mantle.

Spiral tank

The height/diameter ratio of the tank should be about 2.

The length of the solar heat exchanger spiral should be about 2 m per m^2 solar collector.

The temperature sensor of the control system of the solar heating system should be placed in the tank on a level with the lowest part of the solar heat exchanger spiral.

The solar collector fluid should flow from the top to the bottom of the solar heat exchanger spiral.

It is difficult to determine the optimal vertical height of the solar heat exchanger spiral as no validated detailed simulation program exists that can take solar heating systems with hot water tanks with high heat exchanger spirals into calculation. Such a program must be able to calculate the complicated heat transfer conditions of high heat exchanger spirals in detail. Also, the mixing of solar-heated water and the above water heated by the auxiliary energy supply system, described in [12], must be calculable. Furthermore, the downward heat transfer caused by thermal conduction through the heat exchanger spiral must be calculable. In [4], provisional investigations have been carried out. These investigations indicate that the solar heat exchanger should not be higher than 2/3 of the height of the solar volume (the tank volume minus the auxiliary volume) when high volume flows are used in the solar collector loop. Investigations in [22] and [23] indicate that the spiral height should be larger when small volume flow rates are used in the solar collector loop.

Finally, it should be mentioned that there should be a possibility of carrying out a flushing out of the tank.

PRE-HEATER

The tank volume should be about 0.8 times the daily hot-water consumption. The tanks should therefore have a volume between 100 l and 200 l.

The insulation thickness should be about 2-3 cm if polyurethane foam is used. Extra insulation has the largest effect around the upper part of the tank.

Mantle tank

The mantle should cover the tank from the top to the bottom.

The height/diameter ratio should be as large as practically possible.

Spiral tank

The length of the solar heat exchanger spiral should be about 2 m per m^2 solar collector.

As for combi stores it is difficult to determine the best spiral height for pre heaters.

HOT WATER TANK PREPARED FOR SOLAR ENERGY

In principle, these tanks should be designed according to the same guidelines as combi stores.

References

[1] "Undersøgelse af solvarmeanlægget Solkit fra Schweiz". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 278, July 1995.

[2] "Solvarmebeholdere. Beslutningsgrundlag for videreudvikling". Lise Boye-Hansen. Thermal Insulation Laboratory, DTU. Report No. 94-21, July 1994.

[3] "Installations- og korrosionsmæssige forhold for mindre solvarmelagre". Søren Østergaard Jensen, Leon Buhl. The Danish Solar Energy Testing Laboratory, DTI Energy. August 1995.

[4] "Små solvarmeforberedte varmtvandsbeholdere - retningslinier for dimensionering". Søren Østergaard Jensen. The Danish Solar Energy Testing Laboratory, DTI Energy. 1994.

[5] "Varmelagring til solvarmeanlæg". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 162, September 1984.

[6] "Varmeovergang for varmevekslerspiraler neddykket i vand". Søren Østergaard Jensen. Thermal Insulation Laboratory, DTU. Report No. 84-10, May 1984.

[7] "Højtydende solvarmeanlæg med små volumenstrømme. Teoretiske undersøgelser". Peter Berg. Thermal Insulation Laboratory, DTU. Report No. 209, March 1990.

[8] "Små low flow solvarmeanlægs ydelser". Simon Furbo & Peter Fagerlund Carlssom. Thermal Insulation Laboratory, DTU. Report No. 221, August 1991.

[9] "Vejrdata for VVS og energi. Dansk referenceår TRY". Bo Andrese, Stig Eidorff, Lars Hallgreen, Hans Lund, Erik Pedersen, Stig Rosenørn, Ole Valbjørn. Danish Building Research Institute. SBI-Report 135, 1982.

[10] "Højtydende solvarmeanlæg med små volumenstrømme. Eksperimentelle undersøgelser". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 205, March 1989.

[11] "Små low flow solvarmeanlæg til brugsvandsopvarmning - status". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 90-7, October 1990.

[12] Varmelager med omrøring. Prøvning og beregning af Batecs varmelager". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 90-04, February 1994.

[13] "Solvarmebeholdere med kedel-back-up - Dimensionering og driftsforhold". Ivan Katic og Otto Paulsen. The Danish Solar Energy Testing Laboratory, August 1993.

[14] "Undersøgelse af trykløs forvarmebeholder til solvarmeanlæg". Ivan Katic. The Danish Solar Energy Testing Laboratory, October 1994.

[15] "Billige solvarmeanlæg ved sammenkobling med eksisterende varmtvandsbeholdere". Peter Vejsig Pedersen. Cenergia Energy Consultants, November 1994.

[16] "Solvarmeanlæg med standard varmtvandsbeholder som varmelager". Peter Fagerlund Carlsson. Laboratoriet for Varmeisolering, DTU. Report No. 216, November 1990.

[17] "Optimal udformning af low flow solvarmeanlæg". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 238, December 1992.

[18] "Temperaturstratificering i varmelagre". Peter Fagerlund Carlsson. Thermal Insulation Laboratory, DTU. Report No. 238, December 1992.

[19] "Varmelager med cirkulationsledning. Prøvning af Aidt Miljøs varmelager". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 93-2, January 1993.

[20] "Varmelager med cirkulationsledning. Prøvning af Djurs Solvarmes varmelager". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 93-10, March 1993.

[21] "Beregnede ydelser for solvarmeanlæg med cirkulationsledning". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 94-7, February 1994.

[22] "Canadian/Dutch/Danish cooperation on low flow solar heating systems". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 95-3, January 1995.

[23] "Fordele ved små volumenstrømme i solvarmeanlæg. Måling på 3 små brugsvandsanlæg". Simon Furbo. Thermal Insulation Laboratory, DTU. Report No. 188, December 1987.